Enhanced Collision Resolution for the IEEE 802.11 Distributed Coordination Function

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Abstract

The IEEE 802.11 standard relies on the Distributed Coordination Function (DCF) as the fundamental medium access control method. DCF uses the Binary Exponential Backoff (BEB) algorithm to regulate channel access. The backoff period determined by BEB depends on a contention window (CW) whose size is doubled if a station suffers a collision and reset to its minimum value after a successful transmission.

BEB doubles the CW size upon collision to reduce the collision probability in retransmission. However, this CW increase reduces channel access time because stations will spend more time sensing the channel rather than accessing it. Although resetting the CW to its minimum value increases channel access, it negatively affects fairness because it favours successfully transmitting stations over stations suffering from collisions. Moreover, resetting CW leads to increasing the collision probability and therefore increases the number of collisions.

Since increasing channel access time and reducing the probability of collisions are important factors to improve the DCF performance, and they conflict with each other, improving one will have an adverse effect on the other and consequently will harm the DCF performance.

We propose an algorithm, Enhanced Collision Resolution Algorithm (ECRA), that solves collisions once they occur without instantly increasing the CW size. Our algorithm reduces the collision probability without affecting channel access time. We also propose an accurate analytical model that allows comparing the theoretical saturation and maximum throughputs of our algorithm with those of benchmark

algorithms. Our model uses a collision probability that is dependent on the station transmission history and thus provides a precise estimation of the probability that a station transmits in a random timeslot, which results in a more accurate throughput analysis.

We present extensive simulations for fixed and mobile scenarios. The results show that on average, our algorithm outperformed BEB in terms of throughput and fairness. Compared to other benchmark algorithms, our algorithm improved, on average, throughput and delay performance.

Declaration

I declare that this thesis is my original work for the degree of Doctor of Philosophy at De Montfort University, Leicester. The research in this thesis is my own, original work, and all sources used are referenced and cited.

Thaeer Ali Mahmoud Kobbaey

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Abbreviations

ACK	Acknowledgement.
ACWC	Adaptive Contention Window Control.
AI	Artificial Intelligence.
AOB	Asymptotically Optimal Backoff.
AP	Access Point.
BCR-CS	Backoff Counter Reservation / Classifying Stations.
BEB	Binary Exponential Backoff.
BO	Backoff.
BSS	Basic Service Set.
CBR	Constant Bit Rate.
CRB	Centralized Random Backoff.
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance.
CSMA/ECA	CSMA with Enhanced Collision Avoidance.
CTS	Clear To Send.
CW	Contention Window.
CW_{max}	Maximum value of Contention Window.
CW_{min}	Minimum value of Contention Window.
DCF	Distributed Coordination Function.
DIFS	DCF Interframe Space.
DOB	Dynamic Optimisation Protocol.
DSFQ	Distributed Self-clocked Fair Queueing.
DTB	Dynamic Tuning Backoff.
EBA	Early Backoff Announcement.
ECRA	Enhanced Collision Resolution Algorithm.
EIED	Exponential Increase Exponential Decrease.
EIFS	Extended Interframe Space.
EILD	Exponential Increase Linear Decrease.
FCR	Fast Collision Resolution.
GDCF	Gradual DCF.

IBSS	Independent Basic Service Set.
IEEE	Institute of Electrical and Electronics Engineers.
IFS	Interframe Space.
IoT	Internet of Things.
JFI	Jain Fairness Index.
LP	Linear Programming.
MAC	Medium Access Control.
MACAW	Multiple Access with Collision Avoidance for Wireless.
MANETs	Mobile Wireless Ad-hoc Networks.
MCB	Multi Chain Backoff.
MILD	Multiple Increase Linear Decrease.
MPR	Multi-Packet Reception.
MSDU	MAC Service Data Unit.
NAV	Network Allocation Vector.
O-CSMA	Optimal CSMA.
O-DCF	Optimal DCF.
PCF	Point Coordination Function.
PHY	Physical Layer.
PIFS	PCF Interframe Space.
PRMA	Packet Reservation Multiple Access.
QB	Quadratic Backoff.
QoS	Quality of Service.
RAP	Renewal Access Protocol.
RC	Retry Counter.
RF	Re-Transmission Factor.
RT	Re-Transmission Timer.
RT-FCR	Real-Time FCR.
RTS	Request To Send.
SBA	Sensing Backoff Algorithm.
SBE	Slotted Backoff Exponential.
SDB	Semi Distributed Backoff.
SIFS	Short Interframe Space.
SMC	Sequential Monte Carlo.
SPOF	Single Point of Failure.

SRB	Semi-Random Backoff.
STD	Standard Deviation.
TDMA	Time Division Multiple Access.
VANETs	Vehicular Ad-hoc Networks.
VBA	Virtual Backoff Algorithm.
WANET	Wireless Ad-hoc Network.

List of Symbols

$b_{i,k}$	The transition probability to the state (i, k)
CW_i	The CW size in the backoff stage i
$E(Payload)$	The average frame length
m	Maximum backoff stage
n	Number of stations
P	Collision probability in Bianchi's model
P_c	The probability of more than one transmission in a timeslot given that there is at least one transmission in the timeslot
P_d	The probability that no station transmit in a timeslot
P_i	Collision probability in backoff stage i in our analytical model
P_s	The probability of having exactly one transmission in a random timeslot given there is at least one transmission in the timeslot
P_t	The probability there is at least one transmission in the timeslot
T_c	The average time the channel is sensed by a station in case of collision

T_c^*	The average time the channel is sensed by a station in case of collision measured in slot time units
T_{ACK}	Time to send ACK
T_{CTS}	Time to send CTS
T_{DATA}	Time to send the payload packets
T_{MAC}	Time to send MAC header
$T_{PHY_{PH}}$	Time to send PHY header + PHY preamble
T_{RTS}	Time to send RTS
T_s	The average time the channel is sensed by a station in case of successful transmission
τ	The probability a station transmits in a random timeslot
S	Saturation Throughput
S_{max}	Maximum Throughput
s_i	Throughput of station i
σ	Empty timeslot duration

Chapter 1

Introduction

The nature of wireless networks makes them more applicable and easily integrated into our modern needs and trends. Using space as a medium instead of wires provides a more straightforward implementation of such networks, especially in remote locations, historical places, and disaster areas [1]. Many advanced technological solutions rely on the main characteristics of wireless networks (ease of use, mobility, and connectivity) for their implementation, including, but not limited to, Internet of Things (IoT) [2], traffic safety applications [3], and urban environmental research [4].

The increased popularity and applicability of wireless networks sparked the need for a common set of rules for the implementation of wireless networks. The Institute of Electrical and Electronics Engineers (IEEE) came up with the 802.11 standard [5]. IEEE 802.11 is a set of standards for implementing WLAN computer communication, and it covers both Physical Layer (PHY) and Medium Access Control (MAC) layers. Due to its simplicity and effectiveness, the standard has become widely accepted and implemented in wireless networks around the globe [6–8].

The IEEE 802.11 standard defines two modes of operations in wireless networks. The infrastructure mode in which all communications are coordinated using a centralised component called the Access Point (AP) [6]. In this mode, all stations must be within the AP range to be part of the network, which acts as the interconnection to other networks [7]. The second mode is the infrastructure-less mode, or Wireless Ad-hoc Network (WANET), which is a type of wireless network that relies on no predefined infrastructure and no centralised component such as the AP [6].

In this thesis, we focus on WANETs. In these networks, stations are allowed to join or leave the network on the fly [7], thus allowing more flexibility in the implementation. Contrary to infrastructure networks, stations do not need to be in the range of the AP to be part of the network. This feature enables WANETs to extend freely and cover large areas. Moreover, the decentralised and infrastructure-less nature of WANETs offers mobility and the ability to overcome the Single Point of Failure (SPOF) problem.

Due to these characteristics, WANETs are being used in every current aspect of life such as health care, environment monitoring, marine environment, transportation, agriculture, and traffic control [9–11], as well as future aspects [12] such as smart cities [13] and autonomous vehicles [14, 15]. In addition, the current advancement in IoT [2] and the application of Artificial Intelligence (AI), machine learning, and big data in wireless networks [16] will allow these networks to be an integral component of our lives.

Though decentralisation and the lack of infrastructure are the main positive characteristics of WANETs, the absence of a centralised coordinator introduces the problem of coordination and regulating channel access among competing stations [17, 18]. In these networks, stations are independent and communicate directly with each other. Therefore, an effective distributed channel access control is indispensable.

To regulate the shared physical media among all stations and to prevent, detect and avoid collisions, the IEEE standard [5] specifies two main functions to control channel access. The Point Coordination Function (PCF) is used in infrastructure-based wireless networks, providing a conflict-free service, since the AP handles shared medium access. The Distributed Coordination Function (DCF) is used in infrastructure-less wireless networks where stations are independent.

In this research, we focus on DCF, which uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism to control channel access. Moreover, DCF uses the Binary Exponential Backoff (BEB) function, which controls the Contention Window (CW) increment/decrement to reduce the collision probability and improve the channel access time [5].

1.1 Motivation

Following the rapid development of a broad spectrum of applications that operate over WANETs, requirements have dictated fair channel access, massive data transfer rate, and involvement of a large number of competing stations. Based on such rapid deployment of WANETs, the need to improve DCF performance is essential and crucial since several studies concluded that the DCF performance degrades as the number of stations increases [19–23]. Moreover, the continuous improvement in PHY layer specification (increased data transfer rate and Quality of Service (QoS) improvement in real-time applications)[24] has not been matched with the same intensity in MAC layer protocols [25–27].

The DCF process is simple and direct: DCF uses CSMA/CA to regulate channel access. The mechanism of CSMA/CA dictates that stations wishing to transmit must sense the physical medium (channel) first and verify if the channel is idle for a predetermined period equal to their respective Backoff (BO) times [5].

DCF adjusts the BO value randomly using the BEB function. For each station, BEB updates BO with a random value from the range zero to CW. The initial value of CW equals the Minimum value of Contention Window (CW_{min}). The station then proceeds to sense if the channel is idle while reducing its BO timer by one at each timeslot. Once BO equals zero and the channel is idle, the station is allowed to transmit. If an Acknowledgement (ACK) is received, then the transmission is successful, and BEB resets CW to its minimum value.

If the Clear To Send (CTS) or ACK are not received, which will occur if two or more stations picked the same random value for their respective BO or if the RTS, CTS, or ACK frames were lost, BEB doubles the CW size to reduce collision probability in the retransmission and proceeds to update the BO timer for colliding stations. The CW increment continues upon collisions until it reaches the value of Maximum value of Contention Window (CW_{max}).

In our research, we concluded that to improve the DCF performance, the implementation of DCF should shift towards achieving collision resolution, rather than just reducing collision probability. Furthermore, DCF should include a method to improve channel access since its current operation makes the channel remain idle for a significant amount of time.

Another motivation for this work is the lack of IEEE 802.11 analytical models that can anticipate DCF behaviour accurately. Existing analytical models follow the same framework of Bianchi's Markov chain model [20, 28]. Bianchi's model assumes that the collision probability for a station is independent of the CW size and the transmission history of the station. We believe that these assumptions lead to an inaccurate estimation of the state transition probability, thus reducing the accuracy of the throughput analysis.

1.2 Problem Statement

Though BEB is simple and direct, it suffers from the following limitations:

- **The exponential increase in CW.**

  The double increase in CW upon collision reduces the channel access time. Since the CW size is doubled upon collision, the station BO values will increase, and it will spend more time sensing the channel rather than accessing it. Failing to improve the channel access time will reduce the throughput and therefore harm the DCF performance.

  Additionally, since in DCF, collisions are assumed based on the absence of CTS or ACK, which can be contributed to other factors such as packet loss, doubling the CW size based on such an assumption is not justified.

  Moreover, doubling the CW size to reduce the collision probability becomes less effective as the number of active stations increases. For example, doubling the CW size from 31 to 63 will reduce the collision probability by 47% for a scenario of five active station, while for a scenario of twenty active stations, it will reduce the collision probability by 3%.

- **The sudden reset of CW to its minimum value.**

  Resetting the CW to its minimum value upon successful transmission will harm fairness. Since a station with successful transmission will have a smaller CW size compared to a station that suffered a collision, it will have a better chance of accessing the channel.

Regarding the IEEE 802.11 analytical models, we noticed that the vast majority of the suggested models follow Bianchi's framework [29–32]. These models assume a collision probability that is independent of the station transmission history, which yields an inaccurate estimation of the probability τ a station transmits in a random timeslot and therefore results in an inaccurate throughput analysis.

To improve the performance of DCF, we suggest replacing BEB with an algorithm that meets the following specifications:

- **Increase channel access by reducing the channel idle time.** Keeping CW values relatively small will increase channel use, reduce channel idle time, and ultimately increase throughput.

- **Improve fairness by keeping the CW size within range.** Replacing the sudden CW reset with a gentle CW decrease will reduce CW size variation among competing stations and therefore improve fairness.

- **Introduce a method to solve collisions rather than instantly doubling the CW size.** Reducing the collision probability by solving collisions once they occur without instantly doubling the CW size will not harm the channel access time and therefore will improve the throughput. If the collision resolution method does not solve collisions, then we double the CW size.

- **Using a simple and direct method that does not involve complex computations.** The algorithm should maintain the simple process adopted in the [5] standard. Using complex calculations to find an optimal CW value will increase delays and consume energy in the case of sensor networks.

Regarding the IEEE 802.11 analytical models, to provide an accurate throughput analysis, we suggest that an accurate IEEE 802.11 analytical model should take into consideration the station transmission history when adjusting the collision probability.

1.3 Contributions

To address the issues discussed in Section 1.2, we contribute to the body of knowledge as follows:

- **Enhanced Collision Resolution Algorithm (ECRA)**

  To improve the performance of DCF, we develop a new collision resolution method that reduces the collision probability without instantly doubling the CW size. Our method solves collisions once they occur without harming the channel access time by keeping CW values relatively small compared to BEB, and it will double the CW size if and only if collisions reoccur in retransmission.

  We implement our collision resolution method over Exponential Increase Exponential Decrease (EIED) [33]. We opted for an exponential decrease rather than CW reset to maintain fairness among competing stations. Since our algorithm does not increase CW instantly upon collisions and it keeps the CW size small, the exponential decrease will not affect the channel access time. Our collision resolution method is scalable and can operate over different increment/decrement mechanisms.

  Our algorithm is simple and direct and does not involve any complex calculations or estimations. We use two new variables to calculate the CW for each station: CW_{temp}, a variable used to store a temporary value picked from the range $[0, CW_{max}]$, and Re-Transmission Factor (RF), with an initial value equal to CW_{min}.

  Each station will pick a value to update its CW by dividing CW_{temp} by RF. If a collision occurs, the station will reduce the collision probability by updating CW with the value of CW_{temp} mod RF (the division remainder) rather than instantly doubling the CW size, as in BEB. Using our method guarantees that a collision will reoccur only if two or more stations picked the same value from the range 0 to CW_{max} to update their CW_{temp}. If a collision reoccurs in retransmission, then the CW size is increased. Chapter 3 details our Enhanced Collision Resolution Algorithm (ECRA).

- **Accurate Markov Chain Analytical Model**

  We develop a dynamic Markov chain model for IEEE 802.11 DCF under saturation conditions. Our model extends existing models by using a variable collision probability value that is dependent on the station transmission history. We prove that using a collision probability that is independent of station transmission history leads to inaccurate results that do not reflect the actual state transition probability and thus offers an inaccurate throughput analysis.

  Using our model, we develop a novel method to calculate the probability τ that a station transmits in a random timeslot as a function of the number of stations. In our model, the values of τ reflect the transmission history, the CW size, and the number of active stations. Furthermore, our model provides a new approach to calculate τ for each backoff algorithm. Chapter 4 details our analytical model.

1.4 Research Methodology

To evaluate the performance of our proposed algorithm, we adopt the following research methodologies:

- **Performance Simulation.**

  We implement ECRA in Qualnet simulator [34]. More recently, Qualnet has been widely adopted for wireless network simulations due to its ease of use and robustness; see, for example, [35–37]. We present numerous scenarios reflecting different network conditions related to our work. Full details are presented in Chapter 3.

- **Theoretical Analysis.**

  To theoretically evaluate the performance of our proposed algorithm, we follow the framework of the widely used Bianchi's model [20, 28]. We realise that Bianchi's model operates under the decoupling approximation and uses a constant collision probability independent of the current CW size. Such approximations affect the accuracy of our results assuming the required scalability of the network. Therefore, we develop a novel analytical model to evaluate our proposed algorithm performance. Our model uses a variable collision probability dependent on the CW size.

1.5 Thesis Organisation

The thesis is organised as follows:

Chapter 2 presents the background and a review of the literature related to the contributions of the thesis. We present a brief introduction of wireless networks, IEEE 802.11, and DCF. To cover most of the ideas proposed in research, we provide a comprehensive review of the state-of-the-art backoff algorithms. We present the state of the art in IEEE 802.11 analytical modelling as it relates to our proposed model.

In Chapter 3, we present our algorithm. We provide an extensive description of the algorithm and its main operations. We introduce the simulation settings and performance metrics. We explain the simulation scenarios in detail and present results of the benchmark algorithms and ECRA using various fixed and mobile scenarios.

Chapter 4 describes our analytical method. We compare the performance of BEB using our analytical model to that of BEB using Bianchi's model. We also analyse the performance of the benchmark algorithms and ECRA by implementing each of these algorithms using our model.

Finally, Chapter 5 concludes the thesis and suggests future work.

Chapter 2

Background and Literature Review

This chapter discusses the related background and the literature state of the art as it relates to the contribution of this thesis. The chapter consists of three sections. Section 2.1 introduces the two main categories of wireless networks in addition to DCF. Section 2.2 presents state-of-the-art backoff algorithms, including BEB. Finally, Section 2.3 illustrates the state of the art in analytical modelling used to evaluate DCF performance.

2.1 Introduction

Wireless networks can be categorised into two main modes depending on the network nature [6, 7]. The first is infrastructure mode, in which the network contains a central station called AP. The second is the infrastructure-less mode, or WANETs, which contains no centralised administration point.

In the infrastructure mode (often called Basic Service Set (BSS)) [5, 7], stations are connected to an AP, which is a non-mobile station. In this mode, all communication must go through the AP, which also regulates channel access. The main shortcoming of such networks is related to the requirement for all stations to be in the range of the AP. This limitation restricts the mobility and scalability of such networks. Fig.2.1 shows an infrastructure wireless network.

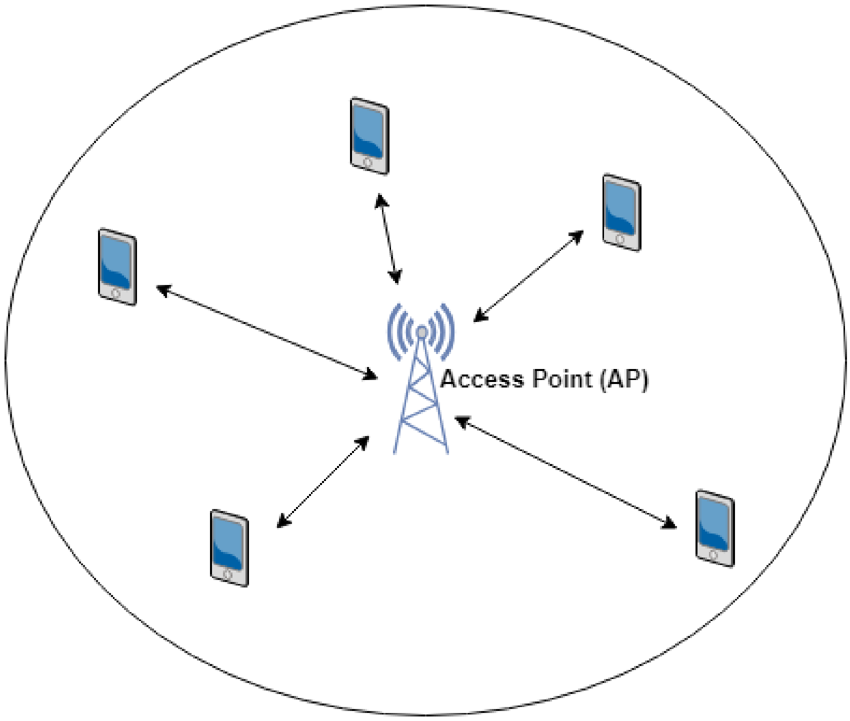

Fig.2.1: Wireless networks BSS mode

In an infrastructure-less mode or WANETs, network (often called Independent Basic Service Set (IBSS)) [5, 7] stations can communicate directly without the need for a centralised component. Stations must be in the range of each other to communicate (single hop) or, if not in direct range, to communicate via other stations (multi-hop). Scalability and mobility are the most important features of this mode since they allow these networks to be integrated and deployed in limitless applications [38]. An infrastructure-less wireless network is shown in Fig.2.2.

The IEEE 802.11 standard [5] provides the set of rules for implementing both modes of wireless networks. According to the standard, sharing the PHY media (channel) among all stations requires a method to regulate channel access to prevent,

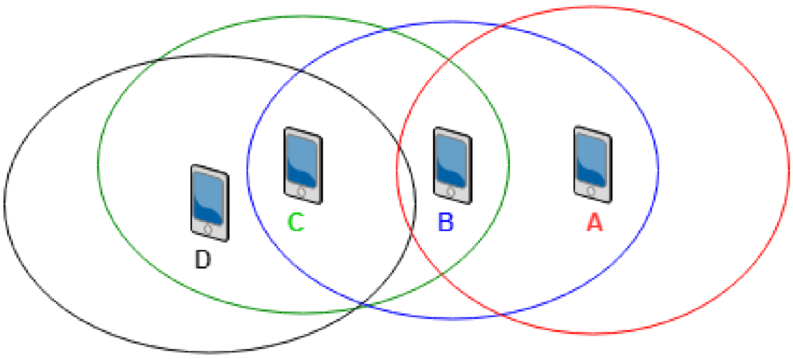

Fig.2.2: Wireless networks IBSS mode

detect, or avoid collisions. The MAC sub-layer regulates channel access using a MAC protocol known as CSMA/CA. The protocol plays a crucial role in scheduling packet transmissions fairly and efficiently among stations [39]. The architecture of the MAC sub-layer (Fig.2.3) consists of two main functions to regulate and control the wireless channel access [8]. The PCF is used in the infrastructure wireless networks to provide a conflict-free service since the AP handles shared medium access.

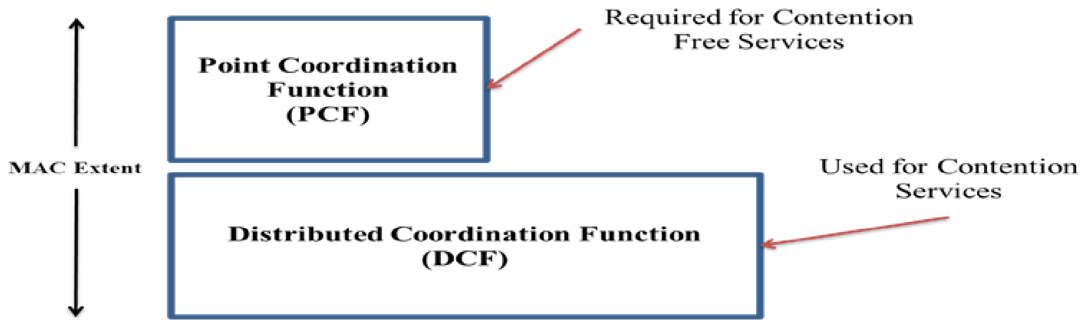

Fig.2.3: Architecture of the MAC sub-layer in 802.11 [5]

The second function, DCF, is used in infrastructure-less wireless networks. In DCF, stations are independent, and the collision probability is high. To add more flexibility, DCF and PCF can co-exist, and the two methods of channel access can alternate as needed [5]. In this thesis, our primary focus is backoff algorithms; accordingly, we focus on DCF.

2.1.1 Distributed Coordination Function (DCF)

DCF is the basic, and fundamental access method in the IEEE 802.11 MAC protocol [5]. DCF defines two access methods; the basic method employs CSMA/CA along with a two-way handshaking protocol (Data - ACK), as shown in Fig.2.4.

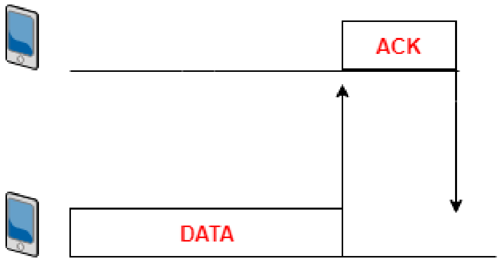

Fig.2.4: DCF basic access mode

The second method is called the Request To Send (RTS) and CTS access method, as shown in Fig.2.5, which employs CSMA/CA along with four-way handshaking access (RTS - CTS - DATA - ACK) [40, 41].

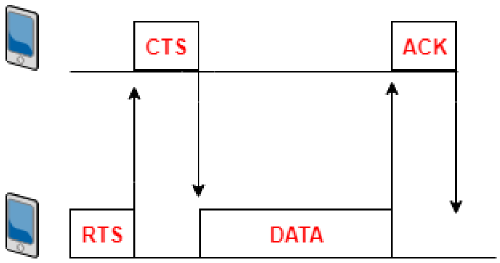

Fig.2.5: DCF RTS/CTS access mode

The RTS/CTS access method was introduced in the Multiple Access with Collision Avoidance for Wireless (MACAW) protocol [42]. The mode was later adopted in the IEEE 802.11 protocol [43–45] and is mainly used when the size of the frame to be sent exceeds a certain threshold [46].

The main setback of the CSMA/CA protocol is the hidden station problem (Fig.2.6) [47]. In such a scenario, stations A and C are not in the range of each other. The problem occurs when A is sending frames to B. In such a case, station C is unaware of any transmission and tries to send to station B; hence, a collision occurs. The carrier sense becomes useless in this case since both stations assume that the channel is idle.

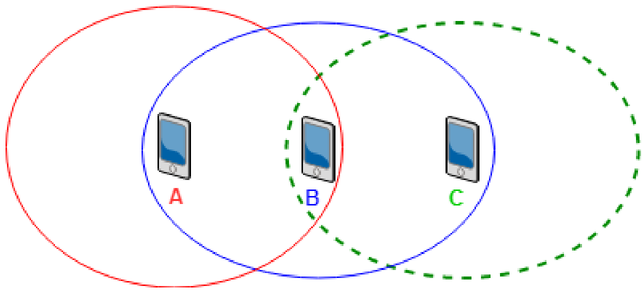

Fig.2.6: Hidden station problem

RTS/CTS provides a solution for the hidden station problem [45] since the use of RTS/CTS by the sender and the receiver announces to their neighbours that the channel is busy. Fig.2.7 illustrates this scenario, where stations in range of both A and B will realise that the channel is not idle upon hearing RTS or CTS.

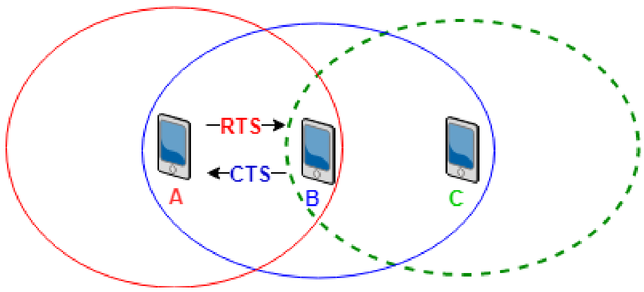

Fig.2.7: RTS/CTS announcement

RTS/CTS also provides means of virtual sensing to detect collisions before starting the DATA transmission. In RTS/CTS, collisions occur only in RTS and are detected by the absence of CTS before the DATA are sent. Since RTS is shorter than the general DATA frame, then using RTS before sending the DATA will reduce the collision duration [20].

The RTS and CTS frames also contain information regarding the transmission duration and DATA size. Upon hearing an RTS or CTS, stations will update their Network Allocation Vector (NAV) accordingly and thus defer their channel sensing. NAV acts as a counter that reflects the channel status, where a zero value means that the channel is idle and a non-zero value implies that the channel is busy.

The CSMA/CA protocol operates as follows: a station wishing to transmit must first sense if the channel is idle for a predetermined amount of time called Interframe Space (IFS). IFS designates the time interval between frames, and the type of frame the station is sending determines which IFS will be used [5]. The shorter the IFS, the more priority it has since it allows the station to access the channel before other stations. The four types of IFS implemented in DCF are the following [5]:

1. **Short Interframe Space (SIFS)**: The shortest inter-frame, used by stations sending CTS, DATA or ACK. It has the most priority since it allows stations to complete an existing transmission before starting a new one [48].

2. **PCF Interframe Space (PIFS)**: Longer than SIFS, used only by the AP in PCF mode to send a beacon frame.

3. **DCF Interframe Space (DIFS)**: Longer than PIFS, used before sending an RTS. If PCF and DCF are working concurrently, then the AP has priority over any other station.

4. **Extended Interframe Space (EIFS)**: The longest IFS, used when an erroneous frame is detected.

Fig.2.8 shows the priority of SIFS over DIFS. In this scenario, station A sends an RTS to station B at the exact time that station C enters the range of A and B. Since SIFS is shorter than DIFS, it will allow B to send a CTS before C can send an RTS. The IFS priority allows an ongoing transmission to proceed and avoid interference from other stations.

After sensing that the channel is idle for the specified IFS interval, stations proceed to transmit if the specified IFS is either SIFS or PIFS (the frame is either a

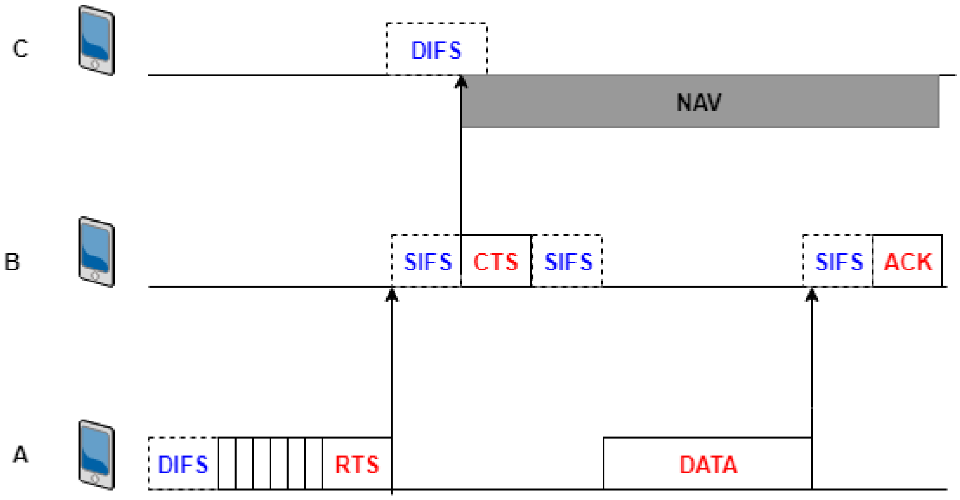

Fig.2.8: Priority of SIFS over DIFS

beacon, CTS, DATA, or ACK). However, if the specified IFS is DIFS (frame is RTS), then stations must sense if the channel is idle for the DIFS duration plus a random period of time (equal to the BO timer) before transmitting. The value of BO is adjusted using the BEB algorithm [5]. Section 2.2 discusses the BEB algorithm in detail.

2.2 Backoff Algorithms

Backoff algorithms are contention-based algorithms used to reduce collision probability in the absence of a centralised component. The main task of a backoff algorithm is to reduce the collision probability and improve the channel access time. Backoff algorithms reduce collision probability by updating the BO of each station with a random value, thus preventing the stations from accessing the channel at the same time. To reduce collision probability, BEB updates BO for each station using a CW value which is doubled if a collision occurs. Another common feature in such algorithms is dividing competing stations into different backoff stages based on the number of collisions they suffered, in addition to other factors [49].

The standard backoff algorithm used in IEEE 802.11 is BEB. It uses a simple process of CW exponential increase and reset to update the BO timer. Several backoff algorithms were suggested to replace BEB, citing many limitations and shortcomings in its operation. These algorithms are discussed in detail in Section 2.2.2.

In this thesis, we present a novel backoff algorithm to solve the limitations of BEB and the related backoff algorithms. This section introduces BEB and the state-of-the-art backoff algorithms. We also identify a benchmark algorithm to be used in the evaluation of BEB and our algorithm.

2.2.1 Binary Exponential Backoff (BEB)

BEB is an algorithm used by DCF to reschedule retransmissions after collisions [5]. The term exponential refers to the exponential increase in waiting time each station must undergo before retransmission. BEB is also called truncated BEB [50] since the exponential increase will stop after reaching a maximum value (Fig.2.9).

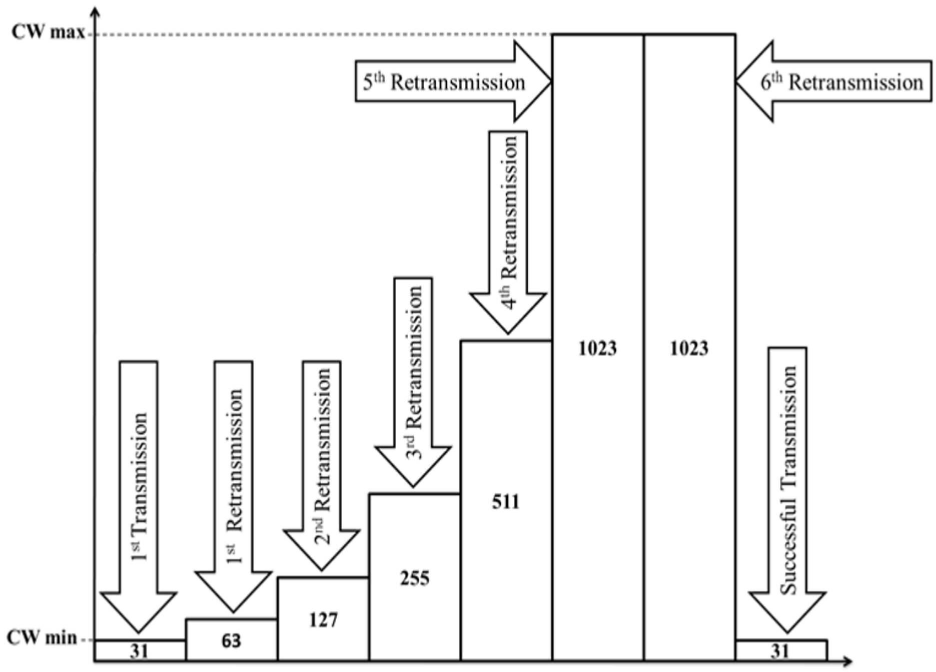

Fig.2.9: Exponential increase in the CW size in BEB [5]

BEB uses the variables CW, CW_{min} and CW_{max} to update the BO timer for each competing station. In IEEE 802.11, the default value of CW_{min} is 31, and for CW_{max}, it is 1023 [5, 51]. The backoff process in BEB is simple and direct and can be summarised as increasing the CW value upon collisions and reducing it upon successful transmission.

In BEB, each station sets the BO timer to $r * \sigma$, where r is a random number in the range from zero to CW and σ is a timeslot. After sensing the channel for a time period equal to DIFS, the station continues sensing whether the channel is idle in each timeslot. If the channel is idle, then the station reduces its BO value by one timeslot. Otherwise, the stations pauses its BO timer (the station will resume its BO timer once the channel is idle again). Once the BO timer reaches zero, the station will be allowed to transmit. The initial backoff process in BEB is illustrated in Fig.2.10.

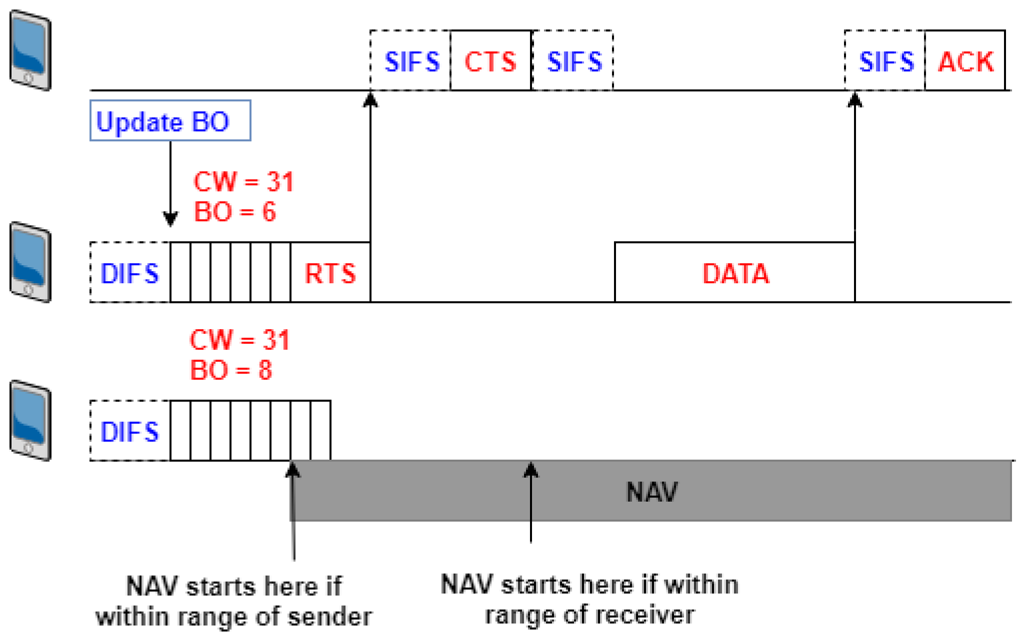

Fig.2.10: Backoff process in BEB

If two or more stations have the same BO value, a collision will occur. In this case, to reduce the collision probability in retransmission, the colliding stations double their CW size, and the BO value is updated using the new CW size, as shown in

Fig.2.11.

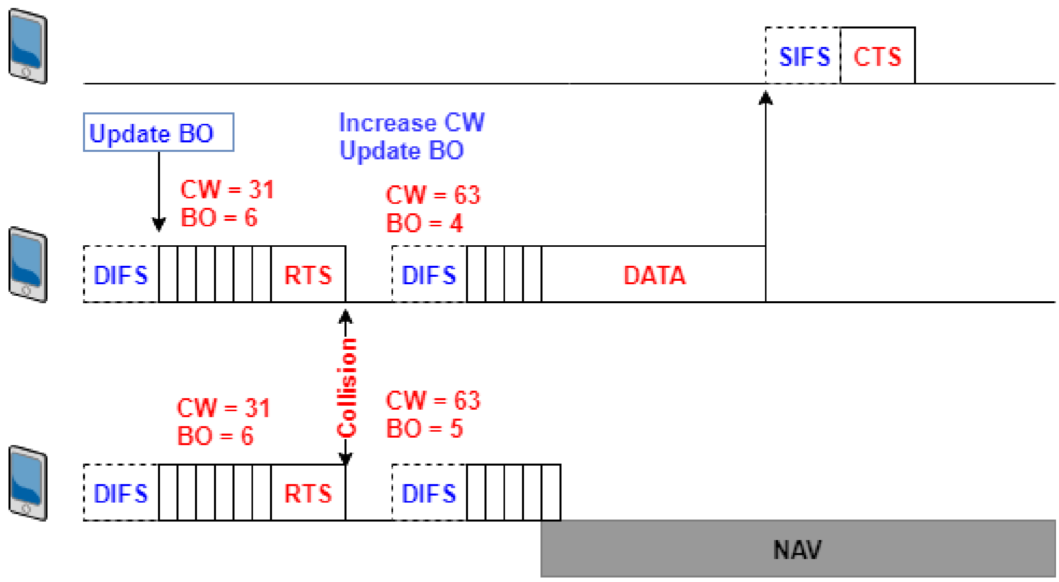

Fig.2.11: Collision avoidance in BEB

The exponential CW increment continues until the transmission is successful or the packet transmission Retry Counter (RC) reaches the retry limit (the retry limit for short packets is 4, and that for long packets is 7) [5]. The value of CW is doubled until it reaches $\mathrm{CW}_{\mathrm{max}}$. Upon a successful transmission, BEB resets the CW to its minimum value ($\mathrm{CW}_{\mathrm{min}}$). Algorithm 1 and Fig.2.12 describe the BEB process in detail.

Algorithm 1. BEB [5]

Input	CW_{max}, CW_{min}, σ
Initialize	$CW = CW_{min}$
Step 1	$BO = rand(0, CW) * \sigma$
Step 2	**while** ($BO \neq 0$ and channel is *idle*) **do**
	$BO = BO - \sigma$
	end while
Step 3	$Transmit$
	if $successful\ transmission$ **then**
	$BO = 0$
	$CW = CW_{min}$
	else
	$CW = \min\left(((CW + 1) * 2) - 1, CW_{max}\right)$
	go to step 1
	end if

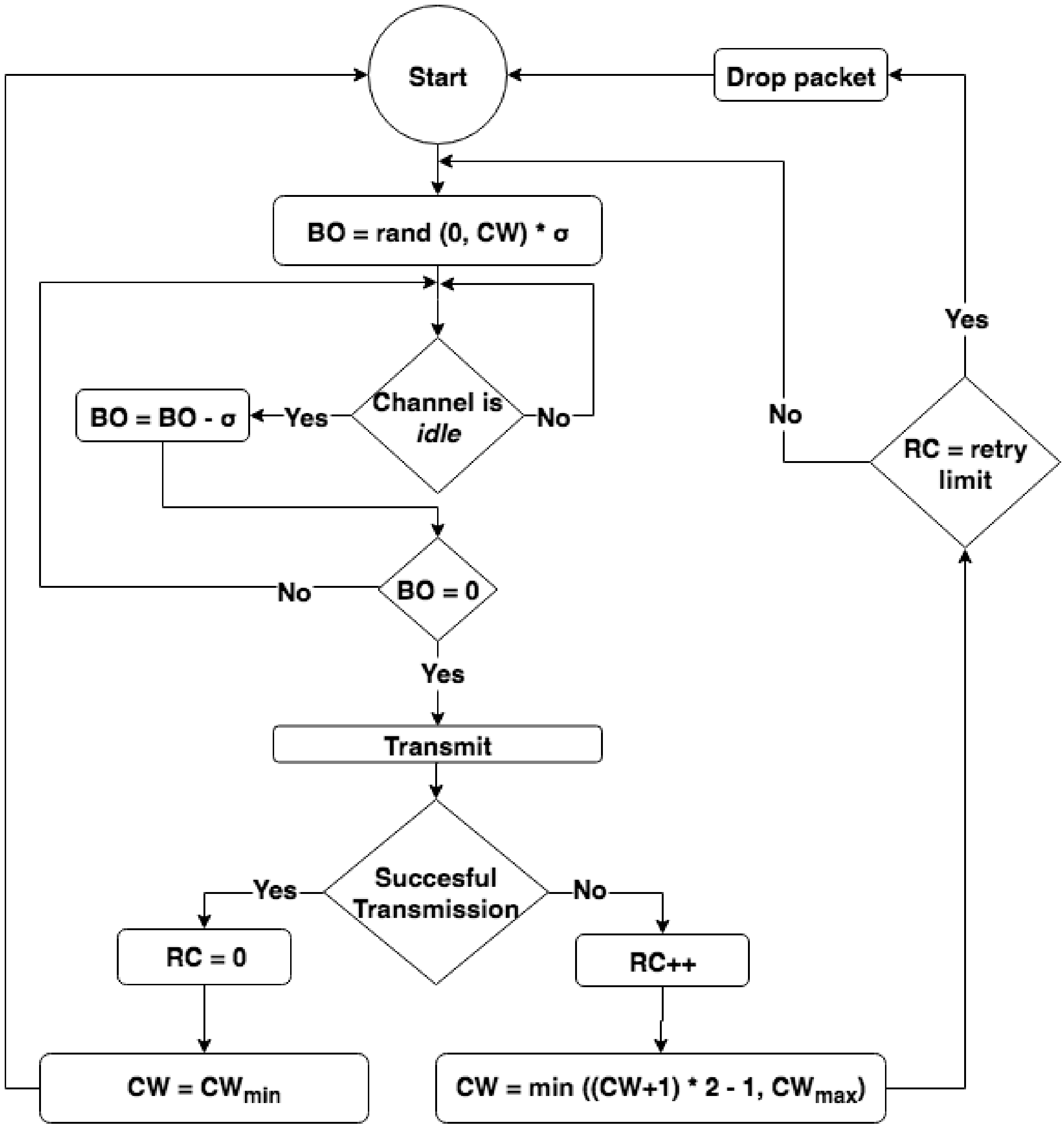

Fig.2.12: BEB flowchart [5]

2.2.2 State-of-the-Art Backoff Algorithms

The shortcomings of BEB ignited research to improve its process and therefore enhance the performance of DCF. Several innovative algorithms attempted to enhance the performance of BEB with respect to many metrics including fairness, throughput, and delay. This section discusses these efforts in detail.

Based on our observations and the available literature, we conclude that to improve throughput and delay, an algorithm must aim to reduce collisions and improve the channel usage time. The challenges rely on the fact that these two aims conflict with each other; achieving one will negatively affect the other. Therefore a compromise has to be considered, as highlighted in [52–54]. The CW increment/decrement operation in BEB is presented in (2.1)

$$CW = \begin{cases} CW_{min} & succesful\ transmission \\ \min(CW * 2, CW_{max}) & collision \end{cases} \tag{2.1}$$

Many researchers have highlighted the degradation in the performance of BEB in WANETs as the number of stations increases [19–23]. This issue makes BEB unsuitable for future implementations of WANETs in which the involvement of a vast number of stations is anticipated [12–16].

The presented algorithms in the literature are split into two main categories. The first category follows the BEB process in using fixed parameters while changing the method of CW increment/decrement. The second category tries to determine an adaptive CW size based on different parameters, such as the number of active stations, the channel status, and the transmission history, along with other parameters.

Early ideas in the first category such as Multiple Increase Linear Decrease (MILD) [55] suggested replacing the exponential increase with a less aggressive increase to improve channel access. Another proposed improvement by MILD is replacing CW reset upon a successful transmission with a linear CW decrement to reduce collisions. Similarly, the work in [56] analyses the effects of a linear CW decrement on throughput.

A similar suggestion was made in [57]. The authors observed that a successful transmission would result in a convenient CW that reflects an optimal CW size.

Therefore, the sudden reset of CW will negatively affect the performance of DCF. This finding changed the direction of research to focus on both CW increase and decrease rather than CW increase only. The CW increment/decrement operation in MILD is summarised in (2.2).

$$CW = \begin{cases} \max(CW - 1, CW_{min}) & succesful\ transmission \\ \min(CW * 1.5, CW_{max}) & collision \end{cases} \tag{2.2}$$

Several works highlighted the exponential increase in the CW size and its sudden reset as the main reasons for the BEB shortcomings. As a result, slower increase and decrease strategies for the CW size were proposed. The work in [33, 42, 58] focused on CW reset suggesting EIED and Exponential Increase Linear Decrease (EILD) algorithms. The processes of EIED and EILD are summarised in (2.3) and (2.4), respectively.

$$CW = \begin{cases} \max(CW/2, CW_{min}) & succesful\ transmission \\ \min(CW * 2, CW_{max}) & collision \end{cases} \tag{2.3}$$

$$CW = \begin{cases} \max(CW - 1, CW_{min}) & succesful\ transmission \\ \min(CW * 2, CW_{max}) & collision \end{cases} \tag{2.4}$$

Focusing on fairness, the Gradual DCF (GDCF) [59] suggests that CW will reset after multiple consecutive successful transmissions. The process of GDCF is summarised in (2.5). Similarly, the work in [60] suggests improving fairness by penalising the successfully transmitting stations with high CW values and rewarding colliding stations with low CW values. This algorithm is summarised in (2.6). In this penalty scheme, the CW increment upon successful transmission can be predetermined or adjusted based on the network conditions.

$$CW = \begin{cases} CW_{min} & C_{st} = c \\ CW & C_{st} < c \\ \min(CW * 2, CW_{max}) & collision \end{cases} \tag{2.5}$$

where c is a predetermined value, and C_{st} is the number of consecutive successful transmissions.

$$CW = \begin{cases} CW_{max} & succesful\ transmission \\ \min(CW * 2, CW_{max}) & collision \end{cases} \tag{2.6}$$

Though the previously discussed methods propose slight changes to the standard and require no complex computations, replacing the exponential increase with a less aggressive one increases the collision probability. Furthermore, using a linear or exponential decrease will reduce the channel usage time since colliding stations will require consecutive successful transmissions to decrease their CW values.

The suggested backoff algorithms in the second category focus on collecting feedback from the network to adjust the CW value. Based on the collected feedback, stations will calculate and estimate several parameters, including but not limited to the channel busyness ratio and the number of active stations. The collected feedback will later be used to adjust an optimal CW value that reflects the network status. Based on their main operation, the methods in this category can be further classified into different approaches: channel status observation, timeslot reservation, collision detection and elimination, and estimation of the number of active stations.

An optimal CW value based on the channel status is the highlight of the backoff algorithms presented in [57-70]. The main idea in these algorithms is that stations will continue monitoring the channel to collect information in regard to timeslots, successful transmissions, failed transmissions, timeslot durations and other factors.

The main setback in these methods is that stations must continue sensing the channel to collect the feedback, which consumes times and energy. Another limitation of these methods is the fact that stations will continue updating their feedback even when they are not active.

The Asymptotically Optimal Backoff (AOB) algorithm [61] focuses on the timeslot duration and the average transmitted frame size to adjust CW. Although AOB does not require estimation of any parameter, it assumes that all sent frames have the same size. The idle sense algorithms presented in [62, 63] suggest that stations continue monitoring the channel to identify idle timeslots. Stations will then adjust their CW according to the idle timeslots. A similar concept is adopted in [64].

The work in [65] introduces a channel-based CW adaptation algorithm. In this algorithm, stations adjust an optimal CW value based on the channel busyness ratio, which is calculated using the number of busy and idle timeslots. A similar concept is presented in [66], who use the channel busyness ratio and delay derivation ratio to adjust the CW.

Several algorithms suggest replacing CSMA with Optimal CSMA (O-CSMA) [67–69]. O-CSMA is based on channel sensing, the frame arrival rate, and the queue size. Similarly, in [70, 71], the authors suggest a frame rate approach based on supply and demand. The same concept is used in the Optimal DCF (O-DCF) algorithm presented in [72, 73].

Focusing on improving throughput in dense networks, the algorithm presented in [74] suggests that if the channel is idle, then stations decrement their respective backoff timer with a probability based on channel status. Finally, the work in [75] uses the CW value as an indicator of the channel load. Low CW values indicate that the channel is lightly loaded, while high CW values indicate the opposite. In this algorithm and based on the channel status, CW is decreased after a certain number of successful transmissions and increased after a certain number of failed transmissions.

Though these algorithms provide a useful method to calculate CW based on channel status, they require stations to continue collecting data from the network. Continually sensing the channel will consume the station energy, especially if the station is not interested in transmission. Furthermore, these algorithms assume that all collected data are accurate, ignoring the possibility of packet errors and the effects of hidden stations. Another shortcoming of these methods is the nature of WANETs, which change dramatically in seconds, meaning that the collected data reflect the previous channel status rather than the current one.

Focusing on improving fairness and throughput, the algorithms presented in [20, 71-84] use slots reservation and announcement to create a collision-free environment. In this approach, the main idea is to distribute channel access fairly among competing stations.

The Slotted Backoff Exponential (SBE) algorithm in [76] suggests that each station has a set of timeslots identified as idle. A station is only allowed to transmit in its designated slots. The work in [77] follows the same concept, it also pays attention to fairness by dividing the number of slots equally among stations. The main setback in this method is that it requires knowledge of the number of active stations and assumes that the number of active stations will not change.

The Backoff Counter Reservation / Classifying Stations (BCR-CS) algorithm [78] identifies stations as being in one of the following states: idle if a station is not ready to transmit, continuous if it is ready to transmit but did not announce its BO to neighbours, and reserved if it is ready to transmit and announced its BO to neighbours. In BCR-CS, stations in the reserved state can transmit while other stations update their BO accordingly. The main limitation in this method is that it neglects the hidden station problem and assumes that all stations are in the range of the sender.

Following the same concept, the Early Backoff Announcement (EBA) algorithm presented in [79] suggests that each station announces its future BO value. Upon receiving that information, other stations will pick a different BO value to avoid collisions. The main setback in this approach is the assumption that all stations are in the range of each other, and it neglects the fact that new stations may enter the network. Moreover, this algorithm will end up favouring stations with smaller BO values over ones with high BO values.

The Multi Chain Backoff (MCB) algorithm [80] proposes to divide the backoff stage into multiple chains representing the different network congestion levels. In MCB, a station will update CW upon collisions suffered by itself and its neighbours. The main setback of this algorithm is its complexity, as it requires knowledge of the nearby stations and multiple calculations of the collision probability to move among the different backoff stages and chains.

The Virtual Backoff Algorithm (VBA) [81] dictates that each station should retain a counter; the station then increases the counter by 1 each time it accesses the channel. Each station will be allowed a limited number of channel access thus achieving fairness by providing more stations with a chance to access the channel. The permitted amount of channel access per stations is calculated using the number of stations in the network. The main setback in this algorithm is that it requires knowledge of the number of active stations and assumes that this number will not change. Moreover, the algorithm assumes that all stations are constantly active.

The work in [82] introduces the Semi Distributed Backoff (SDB) algorithm. SDB suggests a dual operation mode, S-mode and R-mode. In this algorithm and upon collision, the receiver updates the BO counter in the retransmission. A major limitation of this algorithm is that it assumes that the receiver is in an optimal condition compared to the sender, ignoring the fact that the receiver might have suffered previous collisions. Moreover, the receiver might not have received the RTS signal and as such might not be aware of an attempted transmission.

The main limitation of the previously discussed algorithms is the assumption that the number of stations is fixed in the long run, and therefore, it is possible to distribute the channel fairly among competing stations. The previous assumption contradicts the very nature of WANETs, in which stations can join and leave on the fly. Another problem with the previously discussed algorithms is that the assumption that all stations are constantly active is incorrect; therefore, inactive stations will obtain a channel share, and they require complex computations, which can affect the energy consumption, especially in sensor networks.

Focusing on an effective and collision-free method to distribute channel access among stations, the work in [83, 84] follows an approach similar to token networks, where the station with successful transmission will identify which station is assigned the channel next. Improving on the previous, the Semi-Random Backoff (SRB) algorithm in [85] forces stations to use their last successful transmission CW values. In the long run, stations will now have unique CW values, which eliminates collisions. The Packet Reservation Multiple Access (PRMA) algorithm presented in [86] and the Learning MAC algorithm presented in [87] follow the same concept using a Time Division Multiple Access (TDMA) scheme.

Following the same concept, the CSMA with Enhanced Collision Avoidance (CSMA/ECA) [24, 88] algorithm aims to guarantee a collision-free environment. In this enhanced collision avoidance, stations with successful transmission will use smaller CW sizes and will be separated based on an index to avoid future collisions. In [89], the authors introduce a Centralized Random Backoff (CRB) algorithm, in which a centralised station addresses BO assignment for other stations.

The works presented in [90–93] follow an approach similar to the collision detection technique used in Ethernet. These algorithms focus on solving collisions by using jam signals and contention elimination rounds. The algorithm in [94] suggests that before transmitting, stations must select a pulse signal. If the selected signal is 0, a station defers, and if it is 1, the station continues to the next round. The work in [95, 96] follows the same approach by using different numbers of elimination rounds. In [97] stations are divided into subsets, with multiple contention rounds for each subset.

The main setback of this approach is the delay caused by the extra elimination rounds that each station must go through. In addition, using jam signals is not a realistic assumption in WANETs since stations are not necessarily in range of each other.

Several methods have focused on the relation between the number of active stations and an optimal CW value [98–103]. These methods assume that an optimal CW value must take into account the number of active stations in a channel. Since the nature of WANETs makes it very difficult to determine the number of active stations [65], these methods use feedback from the network to estimate the number of active stations.

The Dynamic Tuning Backoff (DTB) algorithm introduced in [52, 53] uses very complicated calculations to find an optimal CW value. In this approach, CW is calculated using the channel congestion level and the number of active stations. With fairness in mind, the authors of [104] propose a fair-medium access protocol. In this algorithm, stations collect data from the network to estimate the number of active stations. Then, each station estimates its channel share and the channel share of other active stations before adjusting CW.

In [105], the authors propose two algorithms, Fast Collision Resolution (FCR) and Real-Time FCR (RT-FCR). FCR incorporates several enhancements to the standard algorithm, as it sets CW_{min} to a significantly lower value and sets CW_{max} to a significantly higher value compared to BEB. FCR updates CW for competing stations by monitoring their transmission history as follows: a station with successful transmission will be assigned low CW values, while deferring and colliding stations will be assigned higher CW values.

To improve channel usage, FCR reduces BO exponentially if multiple consecutive timeslots are idle. To achieve fairness, FCR sets a limit for consecutive successful transmissions by a single station to provide remaining stations with a chance to access the channel. RT-FCR is an updated FCR algorithm to improve fairness and QoS for real-time applications. RT-FCR modifies FCR by using the Distributed Self-clocked Fair Queueing (DSFQ) technique presented in [106, 107], in addition to the service differentiation introduced in [108, 109].

The work in [110] follows the same concept as FCR. A factor derived from the number of active stations and retransmission probability determines the optimal CW value. If the channel is idle, then CW decreases by that factor. In case of a collision, CW increases by that factor, and upon successful transmission, a station keeps its retransmission probability unchanged.

Similarly, the Sensing Backoff Algorithm (SBA) algorithm in [111] suggests that upon successful transmission, the sender and receiver decrease their CW values; their neighbours decrease their CW values by a lesser amount, and colliding stations increase their CW values. The CW increment and decrement are updated using a factor derived from the number of active stations. This algorithm assumes that all stations are within range of each other.

The work in [112] uses a Kalman filter to estimate the number of active stations based on the collision probability. The estimated number of active stations is then used to calculate an optimal CW value. This method can achieve good results assuming a fixed number of stations, no hidden stations, and no missing packets, which rarely hold in real WANETs. In [113], the authors use the same method, suggesting a Linear Programming (LP) technique to adjust the CW_{min} based on channel condition, and the estimation of the number of active stations.

Following the same principle, the Dynamic Optimisation Protocol (DOB) in [114] suggests using the Bayesian estimator presented in [115]. The authors suggest that using the Bayesian estimator provides more accurate results for the number of active stations compared to Kalman. The Bayesian estimator is based on the Sequential Monte Carlo (SMC) methodology presented in [116]. Similarly, estimating the number of active stations in a Bayesian manner is the main idea in Multi-Packet Reception (MPR) [117].

In [118], the authors suggest CW optimisation based on geometric densities. Stations have different backoff intervals based on their neighbours and their transmission history. The method requires estimation of the number of neighbour stations and feedback collection from the network.

To improve throughput, the authors of [119] suggest a linear CW adjustment based on the network status and the number of active stations. To maintain fairness, the algorithm restricts multiple transmissions by a single station.

The Quadratic Backoff (QB) algorithm [120] suggests adjusting CW using a polynomial function. The growth rate of the polynomial function is determined based on the channel conditions and the network size. The Renewal Access Protocol (RAP) algorithm in [121, 122] uses a fixed-size CW for all stations, and BO is decreased by one upon a successful transmission only. The main shortcoming of this method is that it assumes a fixed number of stations. This limitation is later addressed in [123], in which the authors suggest the Adaptive-RAP algorithm.

Considering the nature of WANETs and the fact that in such networks, the number of stations is continuously changing, the work in [124] estimates the number of active stations at every time instant. This method consumes time and energy since a station is required to continually monitor the network to estimate the number of active stations.

Finally, the Adaptive Contention Window Control (ACWC) algorithm [125] suggests that each station updates its CW by calculating the collision probability based on the number of active stations. Stations then transmit their CW values to their neighbours. In this algorithm, the CW value will only increase if the collision probability is greater than a certain threshold.

The main limitation in estimating the number of active stations is that it is practically unforeseeable in WANETs, especially at runtime [52, 61, 97, 105, 115]. Moreover, the possibility of estimation errors will result in inaccurate CW adjustments. Another limitation of this approach is that stations must continue estimating the number of active stations at every time instant since in WANETs, that number changes continuously. Furthermore, the assumption that active stations remain active is invalid since in WANETs, stations change their status regularly.

2.2.3 Exponential Increase Exponential Decrease (EIED)

In this research, we chose EIED [33] as our benchmark algorithm. We chose EIED because similarly to our algorithm, EIED follows the same operation of BEB, and contrary to the algorithms discussed in the literature, EIED does not require any feedback collection from the network and does not rely on any estimations. Furthermore, those algorithms require complex computations and dictate that stations should continue monitoring the channel even if they do not wish to transmit, which affects delay and energy consumption.

Similar to BEB, to reduce collision probability in retransmissions EIED employs an exponential increment of CW upon collisions. To maintain fairness among competing stations, EIED replaces the CW reset in BEB with an exponential decrease upon successful transmission. Although the exponential decrease improves fairness because it keeps the stations CW values similar, it reduces the channel access time by increasing the channel sensing time by stations.

Another reason for choosing EIED is that it is used as a benchmark algorithm in many research papers [58, 120, 125–130], which allows us to compare the behaviour of our proposed algorithm to other algorithms.

Since EIED outperforms BEB in terms of fairness and throughput when the number of stations increases in fixed scenarios [58, 120, 125–130], it enables us to highlight the BEB performance degradation when the number of active stations increases, as will be discussed in Chapter 3.

In addition, since our algorithm is implemented using an exponential increment/exponential decrement method, similar to the one used in EIED algorithm, it is essential to compare the performance of our proposed algorithm to that of EIED.

We implemented EIED in the Qualnet simulator according to the process illustrated in Fig.2.13 and Algorithm 2. A comparison of the results of EIED with those of our proposed algorithm and those of BEB is presented in Chapter 3.

Algorithm 2. EIED [33]

Input	CW_{max}, CW_{min}, σ
Initialize	$CW = CW_{min}$
Step 1	$BO = rand(0, CW) * \sigma$
Step 2	**while** ($BO \neq 0$ and channel is *idle*) **do**
	$BO = BO - \sigma$
	end while
Step 3	$Transmit$
	if $successful\ transmission$ **then**
	$BO = 0$
	$CW = \max((CW + 1)/2, CW_{min})$
	else
	$CW = \min(((CW + 1) * 2) - 1, CW_{max})$
	go to step 1
	end if

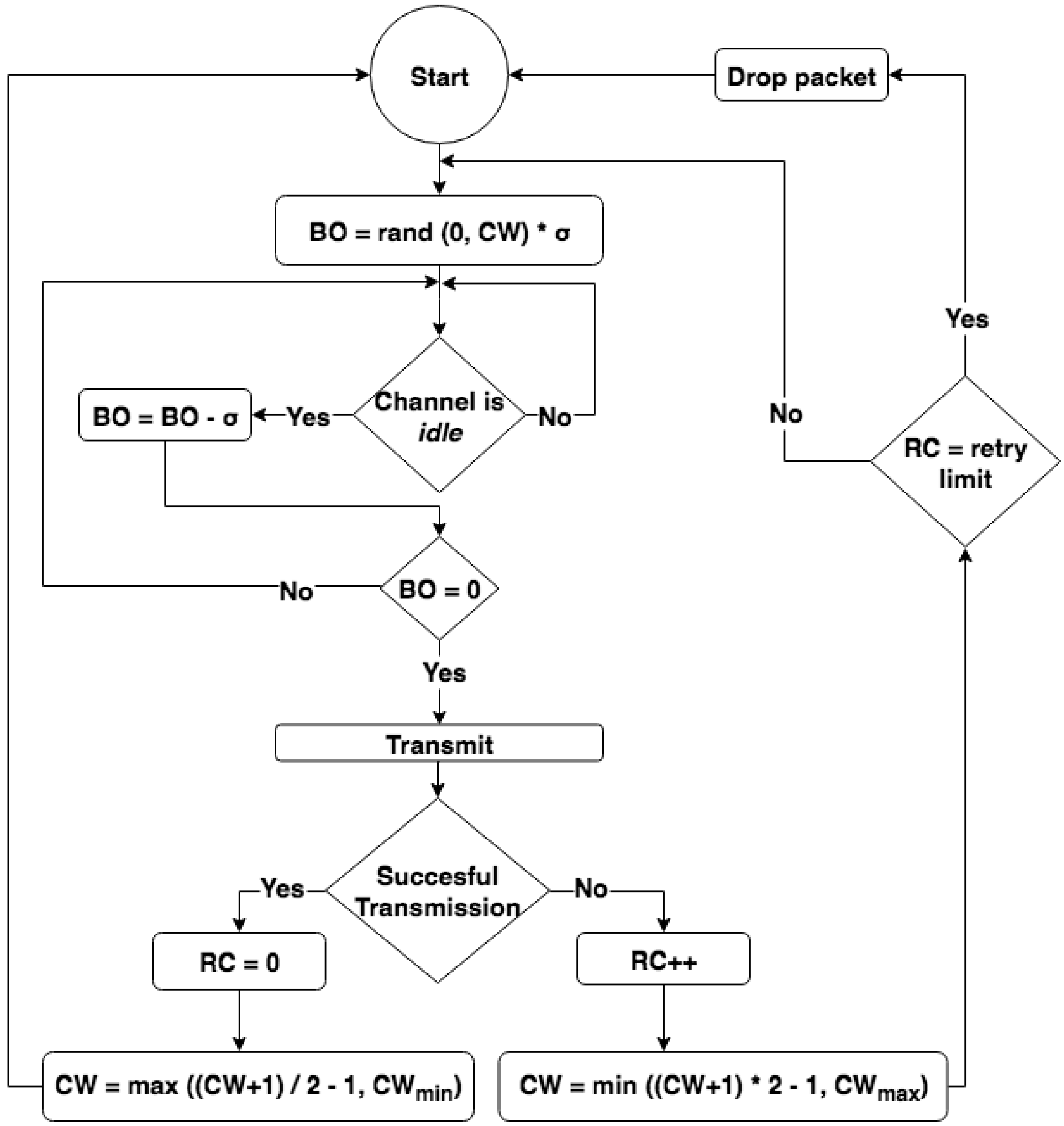

Fig.2.13: EIED flowchart [33]

2.3 Analytical Models

Due to the extensive use of DCF in almost every wireless network [6, 7] and the effectiveness of its CSMA/CA mechanism, several works have proposed theoretical analysis models to analyse the performance of DCF.

The most common DCF theoretical analysis models are the Markov chain-based models, such as Bianchi's model presented in [20, 28]. Another analytical model is the p-persistent model presented in [32, 52, 53] to evaluate the DCF performance under both saturated and unsaturated conditions. The work in [131] presents an average value mathematical model to evaluate the DCF performance. In this thesis, we focus on Markov chain-based models.

A Markov chain model is a stochastic model that describes a sequence of possible events, where the probability of each event depends only on the state attained in the previous event [132, 133]. The stochastic nature of the CW value and BO stages in DCF makes a Markov chain an ideal model to analyse it [28]. Bianchi's model [20, 28] was the first Markov chain-based analytical model to analyse IEEE 802.11 DCF.

2.3.1 Bianchi's Model

Bianchi's model [20, 28] is a Markov chain-based model to analyse saturation and maximum throughput in IEEE 802.11 DCF. The model operates under the following assumptions [20]: decoupling hypothesis, saturated conditions, and ideal network conditions (i.e., no hidden stations and capture [20])

Saturated conditions mean that at every timeslot, a station always has a packet to send [20]. The decoupling hypothesis, in Bianchi's model, can be defined as follows: each station has a constant collision probability at any timeslot, and the collisions at different backoff stages are independent [30, 134], which means that a station has a constant collision probability in any backoff stage regardless of transmission history or the current CW size.

In Bianchi's model, the Markov chain is represented using a state transition diagram (Fig.2.14), where the nodes represent states and the edges represent the transition probability from one state to another.

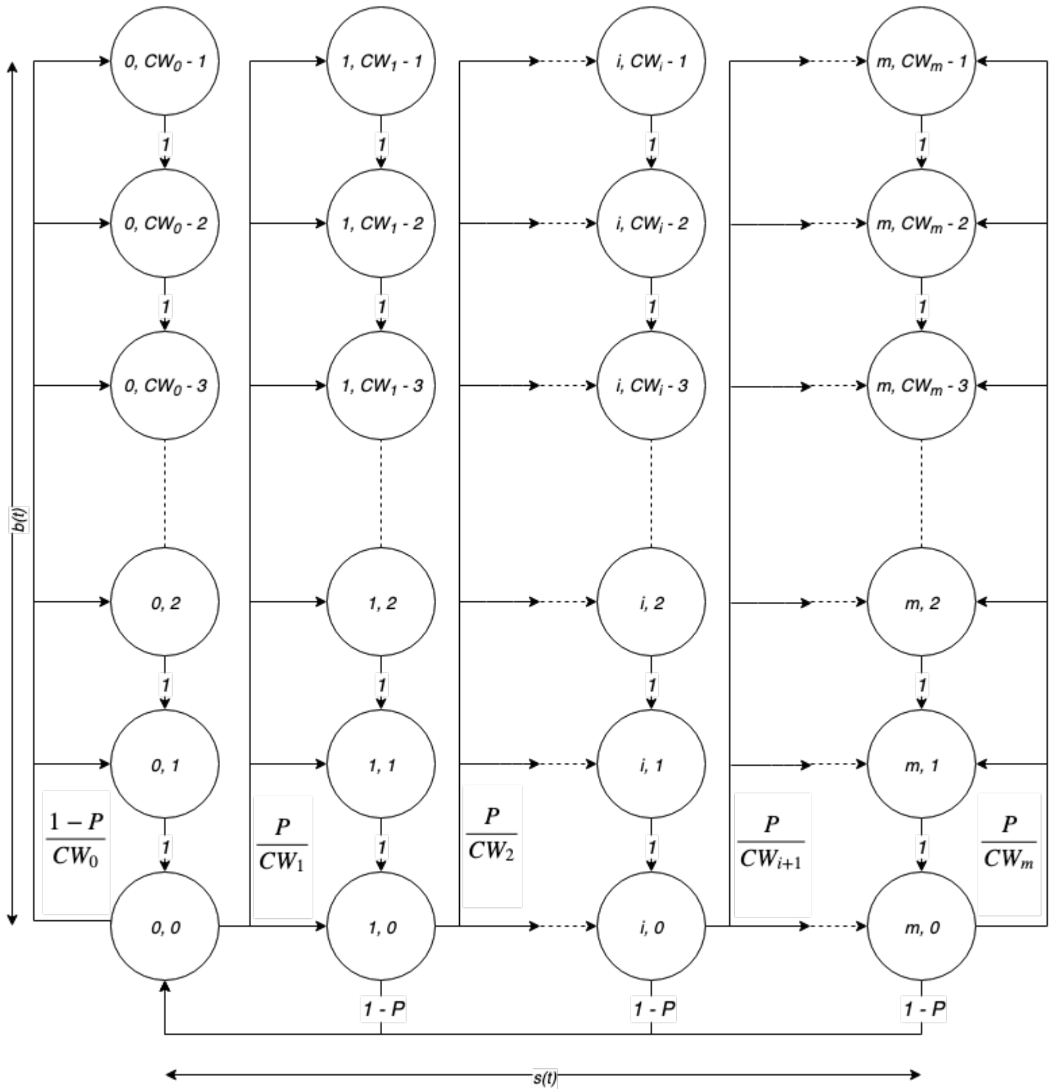

Fig.2.14: Bianchi's model for BEB [28]

Bianchi's model is a general two-dimensional Markov chain with backoff stages from 0 to m (m being the last backoff stage). $s(t)$ is the stochastic process of the backoff stage for a given station at time t, and $b(t)$ is the stochastic process of CW size for a given station at time t. The random BO values for a station can be any value in the range $\{0, \ldots, CW_{i-1}\}$, where $CW_i = 2^i.(CW_{min} + 1)$ [20, 28].

In the state transition diagram shown in Fig.2.14, the states (i, k), where $i \in \{0,\ldots,m\}$ and $k \in \{1,\ldots,CW_{i-1}\}$, represent the stationary distribution of the Markov chain, and it remains unchanged as time progresses [28]. The transition probability to the state (i, k) is denoted $b_{i,k}$ and is given by [28]

$$b_{i,k} = \frac{CW_i - k}{CW_i} \begin{cases} (1-P)\sum_{j=0}^{m} b_{j,0} & i = 0 \\ Pb_{\text{i-1},0} & 0 < i < m \\ P(b_{m-1,0} + b_{m,0}) & i = m \end{cases} \tag{2.7}$$

To evaluate the DCF throughput, Bianchi's model analyses the behaviour of a single station. Since stations can only transmit when their respective BO counter reaches zero, the probability τ that a station can transmit in a random timeslot is [28]

$$\tau = \sum_{i=0}^{m} b_{\text{i},0} \tag{2.8}$$

Since the sum of all states probability equals one, τ is calculated as follows [28]:

$$\tau = \frac{b_{0,0}}{1-P} = \frac{2(1-2P)(1-P)}{(1-2P)(CW+1) + PCW(1-(2P)^m)} \tag{2.9}$$

and the collision probability P equals

$$P = 1 - (1-\tau)^{n-1} \tag{2.10}$$

In Section 4.2, a detailed illustration of Bianchi's model will be presented, as we compare it to our analytical model.

2.3.2 State-of-the-Art Analytical Models

Several analytical models to analyse the DCF performance have been suggested in previous research. Most of the proposed models adopted the same framework as Bianchi's model due to its applicability and predictive accuracy [29]. Those models extended Bianchi's framework to address different network conditions and various CSMA/CA schemes [30, 31].

The models in [46, 135–145] follow the same framework as Bianchi's to analyse the performance of IEEE 802.11 DCF under saturated conditions. The model presented in [135] extended on Bianchi's by suggesting a fixed retry limit in retransmissions similar to the retry limit in the IEEE 802.11 standard [5].

Improving on the previous model, the work in [143] uses a 3-dimensional Markov chain and suggests differentiating between short and long packet retry limits. The main limitation of these models is that the effect of retry limits on DCF throughput analysis is not significant since under saturated conditions; the station constantly has a packet to send.

The effect of the previous backoff stage on the current one is the main idea discussed in [137, 138], where the authors suggest taking into account the current backoff stage and the current backoff counter when calculating the transition probability. The model in [142] extends Bianchi's by introducing the effect of backoff freezes on the DCF analysis. The same concept is presented in [139, 140], where the authors present an analytical model to analyse the throughput and packet delivery ratio.

The main shortcoming of the previous models is that focusing on backoff freezes under saturated conditions will not provide accurate throughput analysis. Since the next timeslot after a successful transmission can only be accessed by the station that successfully transmitted, and the next timeslot after a collision cannot be accessed by any station [5, 146], backoff freezes become insignificant for throughput analysis.

The model presented in [144] extends Bianchi's by adjusting multiple collisions probabilities for multiple consecutive transmissions in a one-dimensional Markov chain. The problem with this model is that these collision probabilities do not take into account the number of active stations in the network. The work in [46, 141] extends Bianchi's by using variable data rates rather than a constant one.

The models presented in [147–150] focus on unsaturated conditions, suggesting that saturated conditions are rarely applicable in WANETs. In [151], the authors extended Bianchi's model by considering the hidden station effect. The models presented in [152–154] extend Bianchi's by assuming non-ideal channel conditions.

The analytical model presented in [155, 156] extends Bianchi's model by considering the effects of dropped packets due to retransmission limits on the average delay. Following the same concept, the models in [157–159] include throughput and delay analysis. A 4-dimensional Markov chain model is introduced in [160], in which the authors integrate a retransmission limit, data load and finite buffer capacity in one model.

Focusing on QoS, [32, 161, 162] suggest extending Bianchi's model to analyse throughput under saturated conditions in IEEE 802.11e. The work in [163–166] extends Bianchi's model to analyse throughput under unsaturated conditions in 802.11e. In [167, 168], the authors extended Bianchi's model by introducing a priority scheme in 802.11 and 802.11e assuming unsaturated conditions.

Several models extended Bianchi's model by focusing on different CSMA schemes. The models suggested in [169–172] focus on multi-hop networks. In [173–179], the presented models focus on 802.15.4 networks and a variety of factors, such as the retry limit and energy consumption. The model in [180] is an analytical model for coexisting 802.11 and 802.15.4. Finally, the model in [181–183] extends Bianchi's by considering different network types and various parameters such as delay and dropped packets.

Most of the suggested IEEE 802.11 models follow the same framework of Bianchi's model and use the decoupling approximation. We highlight the models presented in [137, 144], as they asserted the negative effect of assuming a collision probability that is independent of the station transmission history. In [144], the authors asserted that an infinite number of collision probabilities are needed to accurately represent the behaviour of the IEEE 802.11 DCF.

2.4 Conclusion

In this chapter, we presented a literature review and the background of the work presented in this thesis. We conclude that there are a number of shortcomings that justify our contributions.

Regarding backoff algorithms, we conclude that the current backoff algorithms solve collisions by increasing the CW size to reduce the collision probability. This CW increase leads to reducing the channel access time. To achieve fairness, the state-of-the-art backoff algorithms suggest different CW decrement schemes to provide fair channel access among competing stations.

We provided an extensive discussion of the existing backoff algorithms. To summarise our review, we categorised the backoff algorithms into two main categories. The backoff algorithms in the first category do not change the basic process of the standard but recommend modifications to its CW increment/decrement method. Those algorithms do not require complex computations or feedback collection from the network.

The main limitation of such algorithms is their inability to improve channel access since they suggest a gradual CW decrease compared to that of BEB. These algorithms mainly focus on improving fairness by maintaining the CW within range for all stations, and although they tend to reduce collision probability in highly loaded networks, compared to BEB, they reduce the channel access time by maintaining high CW values. These algorithms suffer in lightly loaded networks since a station will require multiple consecutive successful transmissions to reduce its CW value, therefore significantly decreasing the channel access time.

In the second category, several algorithms suggested collecting different feedback from the network to adjust the optimal CW size. These algorithms suffer many limitations, which can be costly and time-consuming if the selected CW value is miscalculated. One of the main weaknesses of these algorithms is that they require stations to constantly monitor the channel to collect feedback. The continuous channel monitoring will consume stations' time and energy, especially if a particular station does not wish to transmit. Another limitation is the estimations made by these algorithms, which are based on feedback that might not reflect the current status of the channel.

In DCF, collisions are detected based on missing CTS or ACK [184]. Since in WANETs, a missing CTS or ACK can be contributed to other factors such as a lost or erroneous RTS, CTS, and ACK packets, we conclude that increasing the CW size instantly is not justified and is made based on false assumptions. Additionally, we conclude that instantly increasing the CW size upon collision is not the most effective solution regardless of the method used to adjust the new CW.

Regarding IEEE 802.11 analytical models, we conclude that the vast majority of IEEE 802.11 analytical models follow the same framework as Bianchi's model. Most of the analytical models presented in the literature extend Bianchi's to evaluate various network parameters under different network conditions. The vast majority of these models use Bianchi's formula to calculate the probability τ that a station transmits in a random timeslot. Similar to Bianchi's model, these models do not take into account the effect of the station transmission history on the collision probability (P), thus providing an inaccurate estimate of τ, which yields an inaccurate throughput analysis.

In this thesis, we present a new algorithm that reduces the collision probability without instantly increasing CW upon collisions. Chapter 3 details our proposed Enhanced Collision Resolution Algorithm (ECRA). We also present an accurate analytical model that takes into account the station transmission history when computing the collision probability. Chapter 4 details our proposed analytical model.

Chapter 3

Enhanced Collision Resolution Algorithm (ECRA)

In Chapter 2, we detailed the operation of DCF and highlighted that a collision is detected by the absence of ACK and CTS frames [5, 184]. Since a collision can be attributed to other factors in WANETs, as detailed previously, we therefore concluded that increasing the CW instantly upon collisions is not justified since a collision is assumed based on inconclusive parameters. Moreover, we highlighted that increasing CW to reduce the collision probability becomes less effective as the number of stations increases. We also concluded that the CW reset employed by BEB results in unfair channel access, especially for stations that suffered collisions.

Considering the requirements of an effective backoff algorithm detailed in Section 1.2, we present our proposed algorithm, ECRA. In our algorithm, we adopt an approach different from the ones used in the state-of-the-art algorithms. Our algorithm employs a collision resolution method that aims to reduce the collision probability without instantly increasing the CW size, thus improving the channel access time. We design our algorithm to use exponential increment/exponential decrement to maintain fairness among competing stations.

ECRA is simple and direct and does not involve any complicated calculations. We detail the particulars of ECRA and present our simulation results in this chapter.

3.1 ECRA

The main idea in ECRA is using a collision resolution method to replace the instant CW increase. The collision resolution method is used to reduce the collision probability without negatively affecting the channel access time. The collision resolution method in ECRA uses a simple and efficient mathematical principal, based on division and division remainder, to solve collisions among competing stations.

ECRA is simple and direct and does not involve any complicated calculations. In ECRA, in addition to the variables used in BEB (CW_{max}, CW_{min}, and BO), we use three extra variables: CW_{temp}, which holds a temporary CW value between 0 and $CW_{max} - 1$; RF, which is used to calculate the BO value; and Re-Transmission Timer (RT), which is a boolean value used to differentiate a collision resolution state (RT is false) from a normal state (RT is true).

ECRA applies the collision resolution method when RT indicates a collision resolution state (RT is odd). If RT indicates a normal state, then ECRA employs the exponential increment/decrement. The initial value of RT is 0, and RF is set to its maximum value, which is equal to CW_{min}.

In ECRA, if a station wishes to transmit, it must update its CW_{temp} using eq. (3.1). The station then updates its CW using eq. (3.2) if RT is even and eq. (3.3) if RT is odd.

$$CW_{temp} = Randomnumber() \mod CW_{max} \tag{3.1}$$

$$CW = \lfloor \frac{CW_{temp}}{RF + 1} \rfloor \quad (3.2)$$

$$CW = CW_{temp} \mod \lfloor \frac{CW_{max} + 1}{RF + 1} \rfloor \quad (3.3)$$

Fig.3.1 illustrates the ECRA initial process in which RT is even and the station is in a normal state.

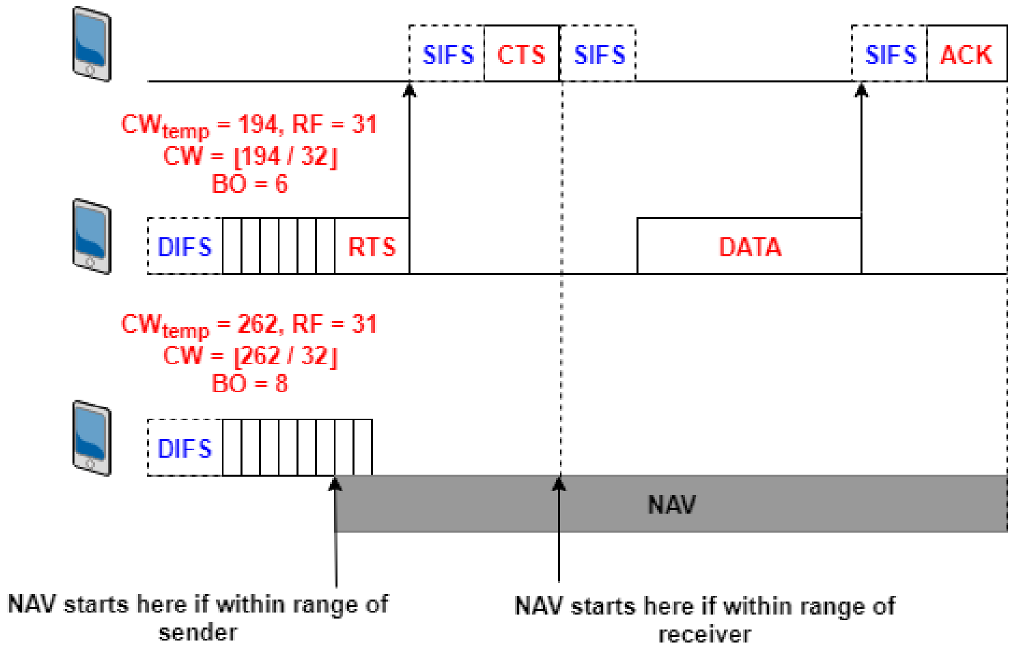

Fig.3.1: ECRA initial backoff process

The ECRA collision resolution method is illustrated in Fig.3.2. Upon collision, the station increases RT counter to enter a collision resolution state while maintaining the same CW size. ECRA reduces the collision probability by using eqs. (3.2) and (3.3); thus, it will guarantee that for a collision to reoccur in retransmission, two or more stations must pick the same value for CW_{temp} from the range from 0 to $CW_{max} - 1$. In BEB, the collision probability is reduced by increasing the CW size.

To illustrate the process, consider a scenario of five active stations. A collision will occur if two or more stations picked the same value from the range from 0 to 31 $(CW_{min} - 1)$. The probability that two or more stations to pick the same number from this range is equal to 0.28. To reduce the collision probability in retransmission, BEB doubles the CW size to 63, thus reducing collision probability in retransmission to 0.15. In ECRA, choosing CW_{temp} from the range $[0, CW_{max} - 1]$ and using RF to calculate the remainder value in retransmission reduces the probability of collision to 0.009 since both stations must pick the same value from $[0, 1023]$ in order for a collision to reoccur.

The previous scenario shows that the collision resolution method in ECRA is more effective at reducing the collision probability compared to the immediate CW increase that BEB uses upon collisions.

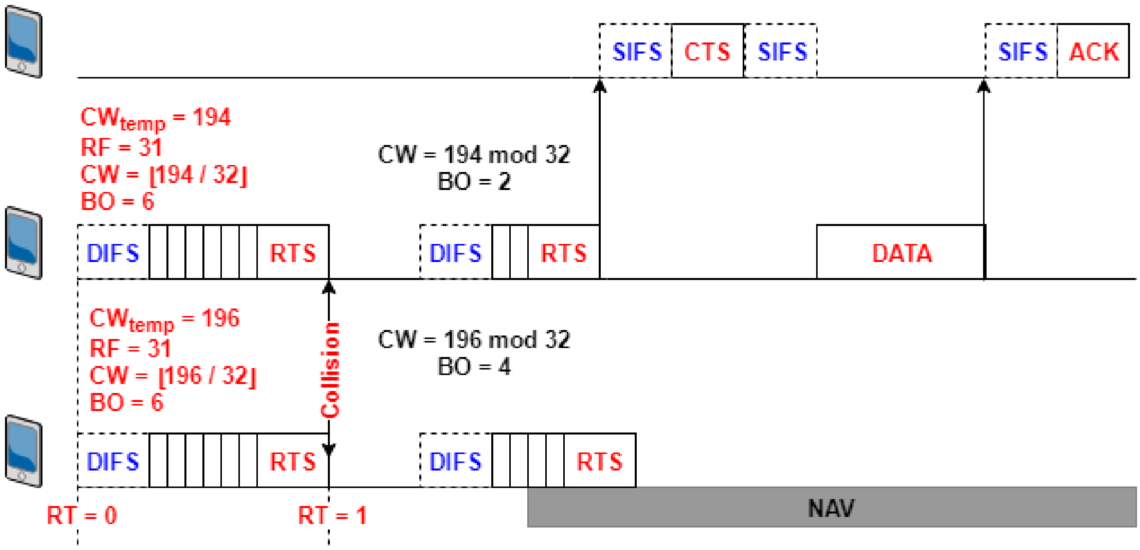

Fig.3.2: Collision resolution method in ECRA

If a collision still occurs, then RT is increased further, entering a normal state (RT is even). In this case, ECRA increases the CW range by reducing the RF size. Each time that RT is even and the station suffers a collision, ECRA increases the CW range exponentially by reducing RF until it reaches its minimum value of two. ECRA increases the CW size if and only if the collision resolution method was not successful.

Upon successful transmissions, ECRA decreases the CW range exponentially by increasing the RF value until it reaches its maximum value, which is equal to CW_{min}. In the meantime, ECRA resets the value of RT to zero, indicating a successful transmission.

In the earlier versions of ECRA, we noticed that during the collision resolution state, interference might occur due to new transmissions within the network. To ensure the effectiveness of ECRA and after several experiments, we opted to update eq. (3.3) by adding the current CW range (eq. (3.4)). By separating colliding stations in contention of their own, this would guarantee no collisions in retransmissions unless the two colliding stations picked the same value from the range from 0 to CW_{max} and no interference from other stations.

$$CW = \lfloor \frac{CW_{max}+1}{RF+1} \rfloor - 1 + CW_{temp} \mod \lfloor \frac{CW_{max}+1}{RF+1} \rfloor \tag{3.4}$$

Using eq. (3.4), we reduce the collision probability for colliding stations without instantly increasing the CW size. Fig.3.3 illustrates such a scenario.

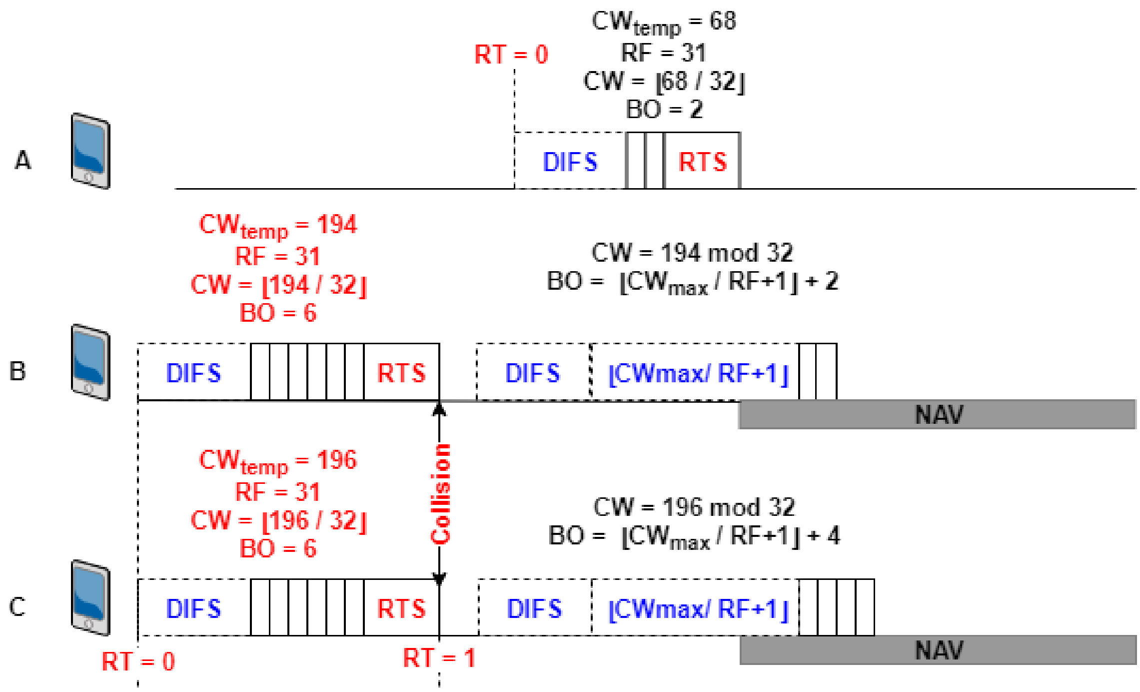

Fig.3.3: Separating colliding stations in contention of their own in ECRA

In this scenario, both stations B and C are suffering a collision, and as such, they enter the collision resolution state. Station A, which is unaware of the collision resolution process, tries to transmit, and since it is separated from both stations B and C, both B and C will add the current CW range to their BO values. Thus, any BO value picked by A will certainly be less than the BO values of B and C. Stations B and C will continue in contention of their own.

The ECRA process and collision resolution method are detailed in Fig.3.4 and Algorithm 3.

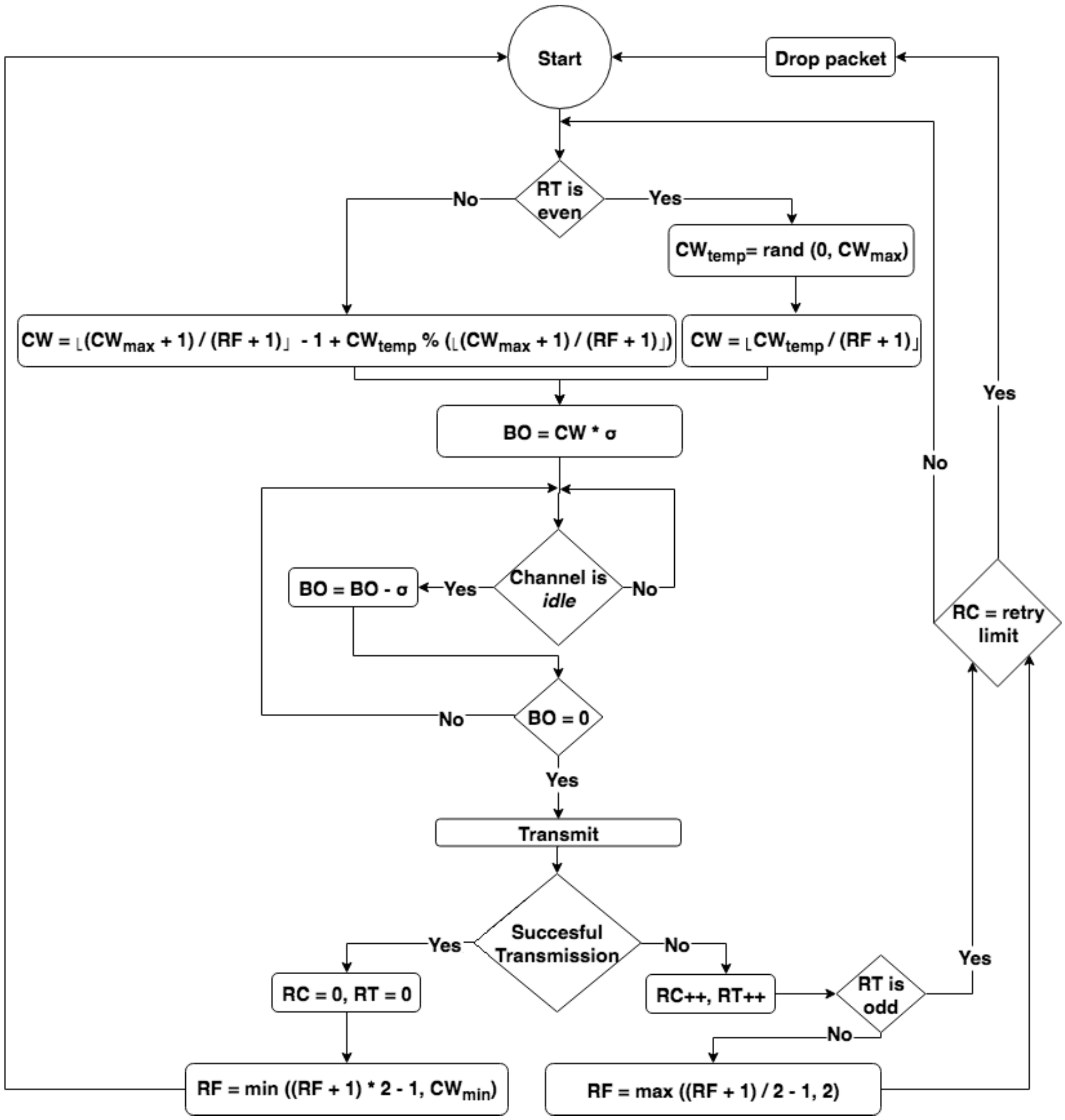

Fig.3.4: ECRA flowchart

Algorithm 3. ECRA

Input	CW_{max}, CW_{min}, σ
Initialise	$RF = CW_{min}, RT = 0, CW = CW_{max}$
Step 1	**if** RT *is even* **then**
	$CW_{temp} = Random()\ mod\ CW_{max}$
	$CW = \lfloor \frac{CW_{temp}}{RF+1} \rfloor$
	else
	$CW = \lfloor \frac{CW_{max}+1}{RF+1} \rfloor + CW_{temp}\ mod\ \lfloor \frac{CW_{max}+1}{RF+1} \rfloor$
	end if
	$BO = CW * \sigma$
Step 2	**while** ($BO \neq 0$ and channel is *idle*) **do**
	$BO = BO - \sigma$
	end while
Step 3	$Transmit$
	if $successful\ transmission$ **then**
	$RF = \min(\lfloor (RF+1) * 2 - 1 \rfloor, CW_{min})$
	$RT = 0$
	else
	if RT *is even* **then**
	$RT{+}{+}$
	go to step 1
	else
	$RF = \max(\lfloor \frac{RF+1}{2} \rfloor - 1, 2)$
	$RT = 0$
	go to step 1
	end if
	end if

3.2 Simulation Settings

We compared the performance of our algorithm to those of BEB and EIED using different simulation scenarios that reflect real-time applications. Appendix A contains a detailed description of our simulation scenarios.

We used QualNet Simulator 7.4, which contains the default BEB algorithm. We used 802.11b parameters for the PHY layer and 802.11 for the MAC layer with a retry limit adjusted to 7 for short packets and 4 for long packets [5]. We used 802.11b specification since all 802.11 variations use the same DCF process. The simulation parameters are reported in Table 3.1.

We used different numbers of competing stations varying from 10 to 50 with an increment of 10. A simulation time of 300 s was picked after trying several simulation times in experiments and concluding that 300 s is sufficient time for the scenario to stabilise. The simulation area is selected based on the station's transmission range to test multiple scenario conditions where stations are close to each other or away from each other. Additionally, the area allows stations to move freely in the mobile scenarios.

We also used 512 bytes as packet size since it gives better results as packets experience less delay and less loss compared to when other packet sizes were tested.

Table 3.1: Simulation parameters in Qualnet

Parameter	**Value**
Simulation Area	1000 m X 1000 m
Simulation time	300 s
Number of Stations (n)	10, 20, 30, 40 and 50
PHY layer	802.11b
Protocol	MAC 802.11
Channel Access	CSMA/CA
RTS / CTS	Enabled
ACK	Enabled
Propagation Delay	1 μs
SIFS	10 μs
DIFS	50 μs
timeslot	20 μs
CW_{max}	1023
CW_{min}	31
Traffic type	Constant Bit Rate CBR
CBR Connections	$n/2$
Packet size	512 Bytes
Packets to send	100
Inter-departure Time	100 μs
Mobility Type	Random Way Point
Minimum Speed	1 m/s
Maximum Speed	10 m/s
Pause Time	0 s

For performance evaluation purposes, we grouped our simulations into five categories according to the number of stations (10, 20, 30, 40, and 50), the reason behind stopping at 50 stations is that the research Qualnet license does not allow using more than 50 stations. For each category, we created 18 scenarios in fixed environments, where stations retain their starting positions until the end of the simulation. We also created 18 scenarios in a mobile environment, where stations are allowed to move. In each category, $n/2$ Constant Bit Rate (CBR) flows were set up where n is the number of stations in that category. In each category, we created scenarios using different topologies: random, grid, and linear (Fig.3.5 and Fig.3.6). We use CBR because it allows us more control over the bandwidth at any moment.

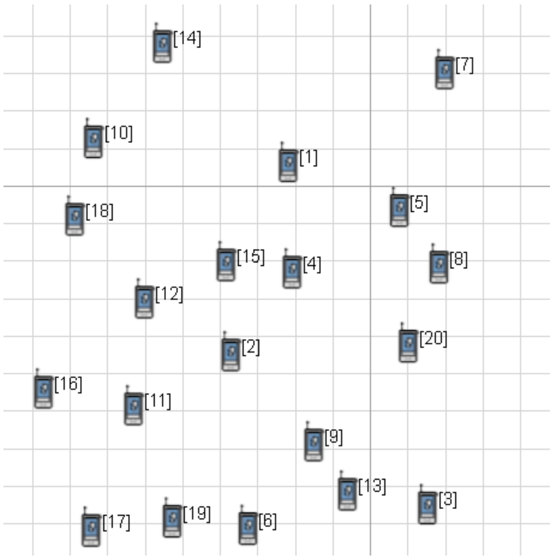

Fig.3.5: Random network topology

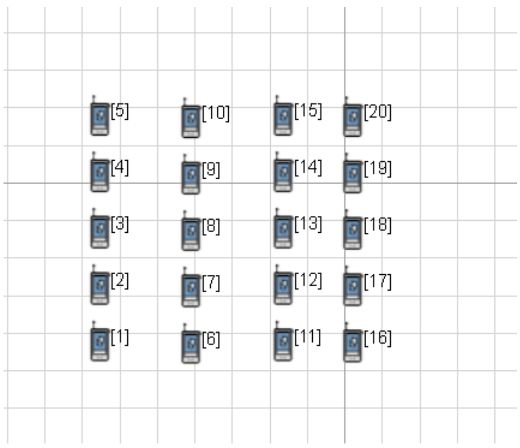

Fig.3.6: Grid network topology

We also used different sending procedures between stations, namely, single-hop and multi-hop. The transmission time was also adjusted. Some stations transmitted at the same time in some scenarios and at random times in other scenarios. In the single-hop scenario shown in Fig.3.7, stations were in the range of each other and could sense each other. In the multi-hop scenario shown in Fig.3.8, stations were not in range of each other and used other stations to send their packets.

Fig.3.7: Single-hop scenario and stations send in pairs

We created scenarios in which stations send in pairs (half the stations are senders, and the other half are receivers), as shown in Fig.3.7. In other scenarios, we adjusted different stations to send to a single station, as shown in Fig.3.7. The latter scenario will increase the collision probability among stations, which will help in studying the performance under heavily loaded conditions.

Finally, we implemented the scenarios in two categories regarding sending time. In the first category, all stations transmit at the same time, whereas in the second category, stations transmit at random times. We ran each scenario 30 times using different seeds to validate the results obtained. A complete set of our simulation scenarios can be accessed using our Mendeley Dataset V1 [185].

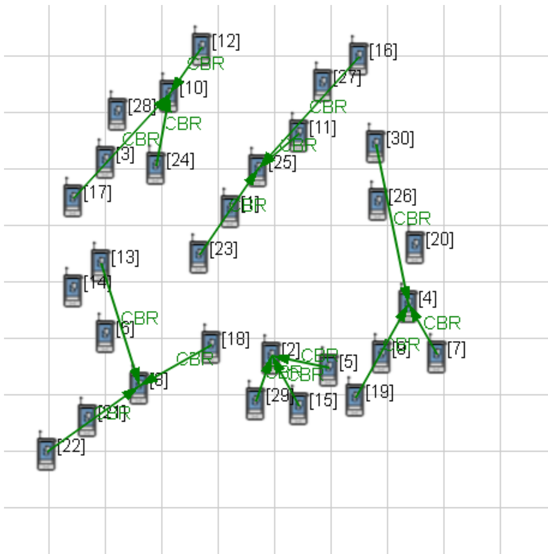

Fig.3.8: Multi-hop scenario in which multiple stations send to one station

3.3 Performance Metrics

In this section, we describe the performance metrics that will be used to compare the performance of ECRA to those of BEB and EIED.

3.3.1 Throughput

Throughput is defined as the number of packets successfully received over a period of time [6]. It is measured in bits per second (bps). In our simulation, we calculate throughput as the average throughput per receiver $\pm$ 1 Standard Deviation (STD). Throughput is as an essential metric of network performance since it represents the actual data transfer rate.

In WANETs, the throughput is affected by the number of collisions and the channel access time. To improve the throughput, a backoff algorithm should increase channel access time and reduce the collision probability.

3.3.2 Fairness

Fairness is one of the most important metrics in backoff algorithms design. A backoff algorithm must guarantee fair channel access among competing stations. In our work, we evaluate fairness using the Jain Fairness Index (JFI) [186], and we we calculate fairness as the average fairness per all stations $\pm$ 1 STD. The JFI is calculated using eq. (3.5) [186]

$$F_{Jain}(s_1, s_2, \ldots, s_n) = \frac{(\sum_{i=1}^{n} s_i)^2}{n \sum_{i=1}^{n} s_i^2} \tag{3.5}$$

where n is the number of active stations and s_i is the throughput of station i.

The main factor affecting fairness in DCF is the CW reset upon successful transmission, which will provide a station with successful transmission with a better channel access chance since its CW size is small compared to a station that suffered a collision.

3.3.3 Delay

The delay is the total time required by the frame to travel from the sender to receiver [6]. In our simulation, we calculate the delay as the average end-to-end delay per receiver $\pm$ 1 STD.

The main factor causing delay is the number of collisions. As the number of collisions increases, the station will suffer a CW increase and less channel access, which will increase the delay.

3.3.4 Jitter

Jitter is the variation in the delay between frames. It is caused by the frame position in the queue or by bandwidth congestion [187].

Jitter affects the performance of the network and the transmission quality, especially in real-time applications. In our simulation, we calculate jitter as an average per receiver $\pm$ 1 STD.

Jitter is caused by the variation in CW sizes among competing stations, which allow some stations more channel access than other stations. To improve jitter, a backoff algorithm must ensure that the stations exhibit slight variation in their CW sizes.

3.4 Fixed Environment Results

In the fixed environment, stations kept their starting positions until the end of the simulation.

3.4.1 Throughput

Fig.3.9 shows that the throughput decreased as the number of stations increased. This increase is due to the increase in collisions, which leads to an increase in the number of packets lost due to the re-transmission limit. Table 3.2 reports the throughput improvement percentages of ECRA and EIED compared to that of BEB.

The results show that BEB performs very well when the number of stations is small. The results also highlight one of BEB's main shortcomings with regard to

Table 3.2: Throughput improvement percentage compared to BEB in fixed environments

	10	20	30	40	50	Average
EIED	-6.6%	-3.9%	-1.8%	1.3%	10.3%	-0.1%
ECRA	-0.4%	-1.0%	0.2%	4.0%	15.4%	3.6%

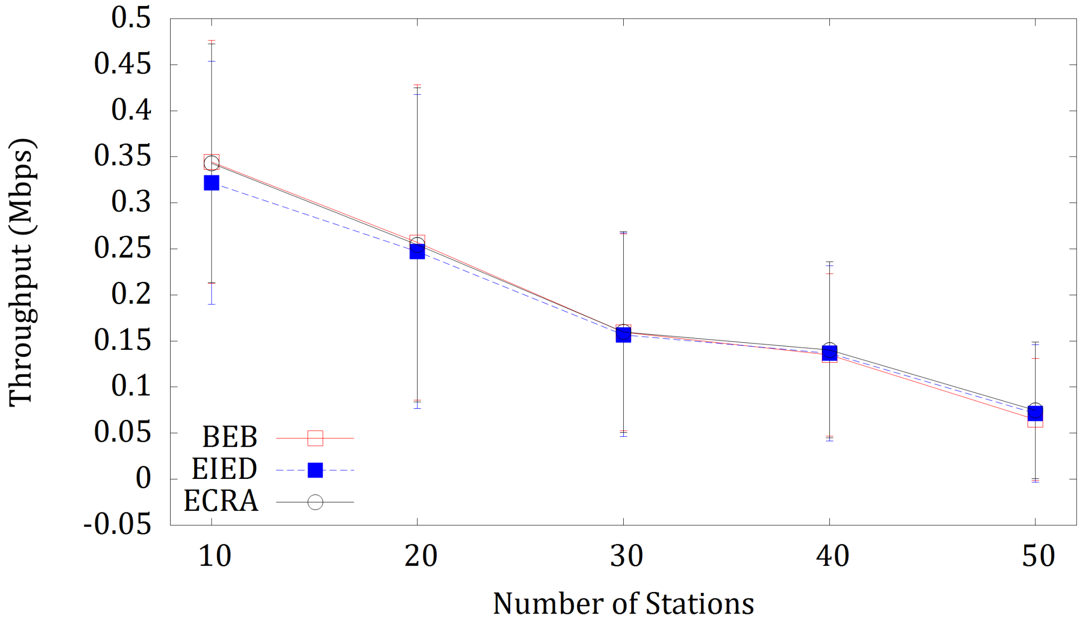

Fig.3.9: Average throughput per receiver in fixed environment ± STD

its performance degradation when the number of stations increases, as is the case in dense WANETs. This limitation is mainly due to BEB's sudden reset of CW upon successful transmission. Although the sudden CW reset increases the channel access time, it increases the number of collisions because it reduces the CW range and increases the collision probability.

Results also highlight another main shortcoming of BEB, which is relying solely on CW increase to reduce the collision probability. Though the CW increase can effectively decrease the collision probability when the number of stations is small, it does not have the same effect when the number of stations is large.

The results also show that ECRA outperforms BEB and EIED as the number of stations increases. It hits a performance peak at 50 stations, with an improvement percentage of 15% relative to BEB and 5% relative to EIED. ECRA also performs well compared with BEB when the number of stations is low. Based on these results, we project that ECRA will continue to outperform BEB and EIED in dense networks in which the number of stations exceeds 100. In our simulation we could not increase the number of stations above 50 because this is the limit allowed by the Qualnet research license.

The throughput results of ECRA and EIED prove that our collisions resolution method is effective since both algorithms employ the same increment/decrement mechanism. The fact that ECRA outperforms EIED highlights that our collision resolution method enhanced the performance of our algorithm and improved throughput by increasing channel access time while reducing the collision probability.

3.4.2 Fairness

The fairness results are presented in Fig.3.10. The fairness improvement percentages of ECRA and EIED relative to that of BEB are reported in Table 3.3.

Table 3.3: Fairness improvement percentage compared to BEB in fixed environments

	10	20	30	40	50	Average
EIED	-2.9%	0.1%	4.0%	9.4%	14.0%	4.9%
ECRA	-0.5%	0.1%	2.7%	2.8%	6.4%	2.3%

The results show that the fairness decreases as the number of stations increases; this is due to the increase in the number of collisions, which leads to an increase in the CW size variation among competing stations and therefore affects the channel access chances.

Results also show that ECRA achieved better fairness than BEB due to its ability to increase the channel access time, which allowed more stations to transmit. It also decreases CW gradually rather than the sudden reset used in BEB.

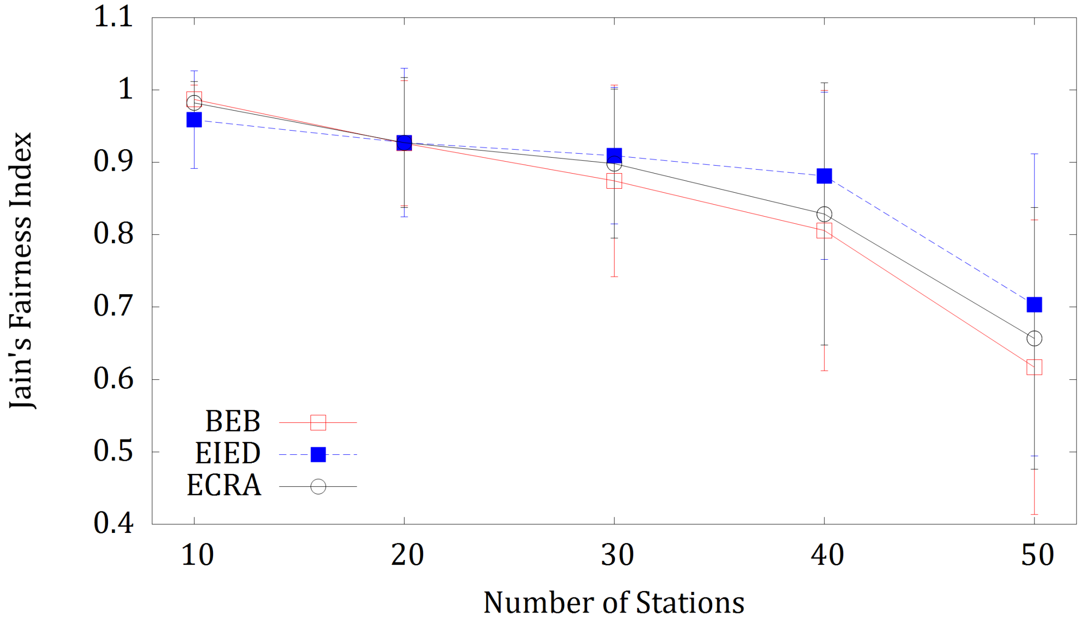

Fig.3.10: Average fairness per receiver in fixed environments ± STD

EIED performs better than ECRA because it increases the CW size for all stations. Though this outcome leads to a very high CW size, it maintains the CW values of most competing stations within a small range, thus allowing fair channel access.

Results also show EIED achieves better fairness results at the expense of increasing the CW size. This outcome leads to less channel access time and will result in an extra delay. ECRA outperforms BEB in terms of fairness since it employs a gradual CW decrease rather than resetting CW to its minimum value.

3.4.3 Delay

The delay results are shown in Fig.3.11, and the improvement percentages of ECRA and EIED relative to BEB are reported in Table 3.4. The results show that the delay increases as the number of stations increases; this is due to the increase in the number of collisions.

Table 3.4: Delay improvement percentage compared to BEB in fixed environments

	10	20	30	40	50	Average
EIED	-13.1%	-16.9%	-13.6%	-10.4%	-22.4%	-15.3%
ECRA	-2.2%	-7.7%	-7.2%	-8.0%	-16.7%	-8.4%

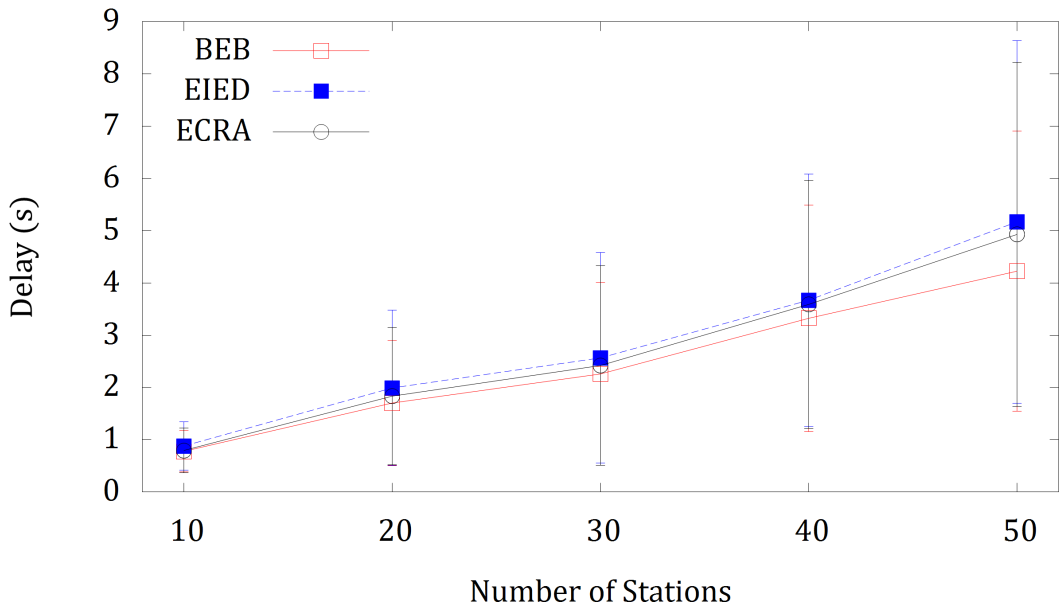

Fig.3.11: Average delay per receiver in fixed environments ± STD

The results also show that ECRA outperforms EIED in all scenarios. Considering that both ECRA and EIED employ the same CW increment/decrement mechanism, the results prove that the ECRA collision resolution method is the main factor affecting the performance.

BEB outperform ECRA and EIED in terms of delay; this is due to the CW reset employed in BEB, which allows successfully transmitting stations more channel access with low CW size. Although the CW reset increases the collision probability, it will allow stations to use lower CW values and thus reduce the delay.

3.4.4 Jitter

The jitter results are shown in Fig.3.12. The improvement percentages of ECRA and EIED relative to BEB are reported in Table 3.5.

Table 3.5: Jitter improvement percentage compared to BEB in fixed environments

	10	20	30	40	50	Average
EIED	-12.3%	-6.8%	23.7%	34.5%	18.8%	11.6%
ECRA	-1.3%	-1.6%	14.1%	6.5%	7.4%	5.0%

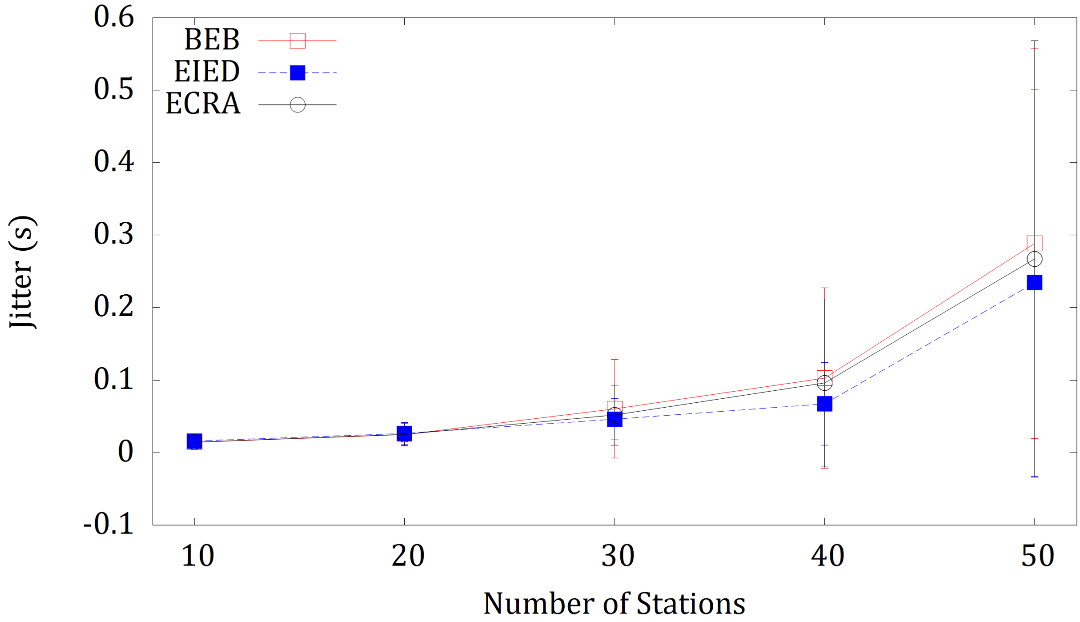

Fig.3.12: Average jitter per receiver in fixed environments ± STD

The results show that the average jitter increases as the number of stations increases, which is due to the variation in CW values caused by the increased number of collisions. ECRA enhances the performance compared to BEB when the number of stations increases due to its increment/decrement strategy and its collision resolution method. EIED outperforms ECRA and BEB because it tends to maintain high CW values amongst competing stations, thus reducing the number of collisions.

3.5 Mobility Environment Results

In this environment, stations moved at various speeds, from 1 m/s to 10 m/s, with the pause time between movements fixed to 0. The various speeds reflect the speed range of a walking human to a slowly moving vehicle.

3.5.1 Throughput

In mobile stations, the throughput results are affected by the constant movement of stations, which results in some stations being out of range. This outcome will cause many frames to be dropped and therefore affect the throughput.

Fig.3.13 shows the throughput results, and the throughput improvement percentages of ECRA and EIED relative to BEB are reported in Table 3.6.

Table 3.6: Throughput improvement percentage compared to BEB in mobile environments

	10	20	30	40	50	Average
EIED	-3.6%	-5.7%	-2.1%	0.8%	-3.3%	-2.8%
ECRA	0.6%	0.3%	-0.1%	1.2%	0.9%	0.6%

The results show that BEB performs better than EIED when the number of stations is low; this is due to the CW reset in BEB, which is effective in lightly loaded networks. Results also show that EIED outperforms BEB as n reaches 40, and EIED performance drops compared to that of BEB as n reaches 50. The main reasons behind this drop is the randomness of the mobile scenarios which causes stations to be our of range of each other as they move, thus resulting packets to be dropped.

The results also show that ECRA performs comparably better than both BEB and EIED specially when the number of stations increases due to its effective collision

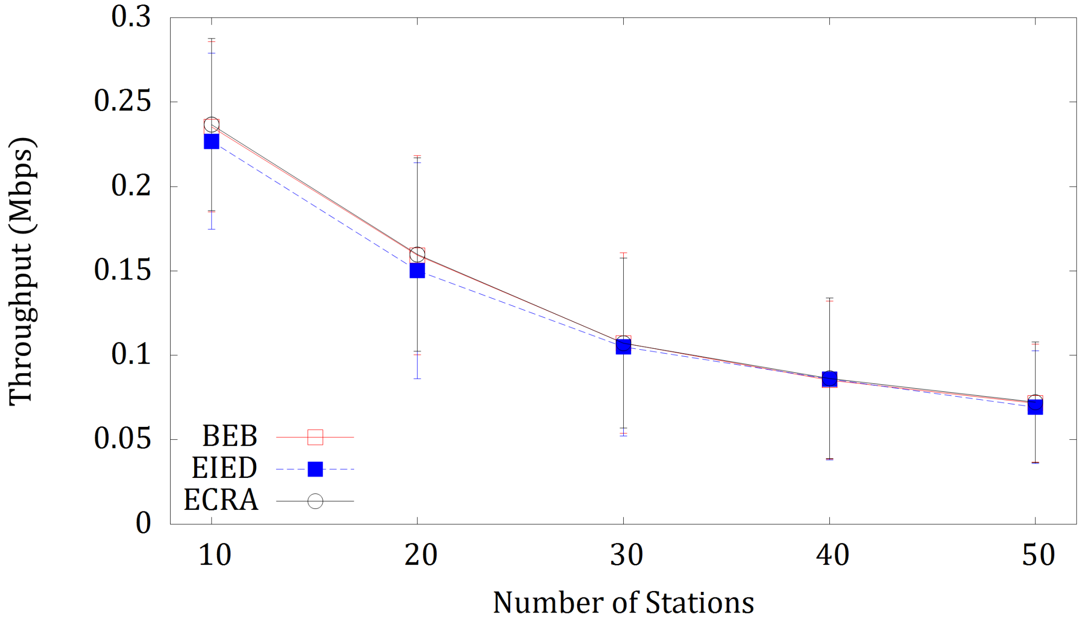

Fig.3.13: Average throughput per receiver in mobile environments ± STD

resolution method operation as Table 3.6 shows. The results also show that the performance of ECRA is not affected by increasing the number of stations, as its performance is improved compared to that of BEB and EIED.

3.5.2 Fairness

The fairness results are presented in Fig.3.14, and the improvement percentages of ECRA and EIED relative to BEB are reported in Table 3.7.

Table 3.7: Fairness improvement percentage compared to BEB in mobile environments

	10	20	30	40	50	Average
EIED	-3.6%	-0.4%	-0.6%	4.4%	3.6%	0.7%
ECRA	-0.4%	2.4%	0.2%	1.7%	-0.2%	0.7%

The nature of station mobility causes some stations to be out of range, which will affect the throughput and therefore the fairness. In a mobile environment, many packets will be lost due to receivers being out of range.

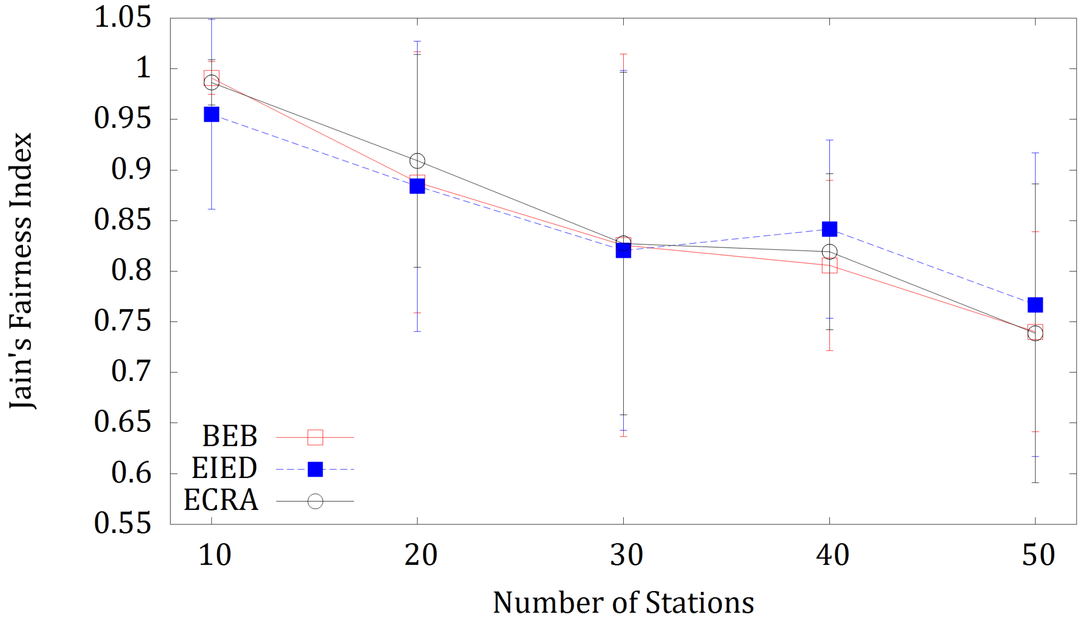

Fig.3.14: Average fairness per receiver in mobile environments ± STD

ECRA outperforms EIED when the number of stations is low but starts to suffer as the number of stations increases. The performance of EIED is partially due to the high CW values assigned to the stations. The fairness and results also highlight the behaviour of EIED, which focuses more on reducing the collision probability than on increasing the channel access time, thus reducing the number of packets lost due to retransmission limits.

On average, ECRA performs similarly to EIED, and both algorithms outperform BEB. The main factor affecting fairness in BEB is the immediate reset of CW to its minimum value upon successful transmission. The performance of ECRA suffers as the number of stations increases since it prefers to maintain a low CW size and focus more on increasing the channel access time.

3.5.3 Delay

The delay results are shown in Fig.3.15, and the improvement percentages of EIED and the proposed algorithm relative to BEB are reported in Table 3.8.

Table 3.8: Delay improvement percentage compared to BEB in mobile environments

	10	20	30	40	50	Average
EIED	-9.1%	-17.8%	-6.0%	-9.6%	-6.3%	-9.8%
ECRA	-1.9%	-6.8%	-0.7%	-12.6%	-7.0%	-5.8%

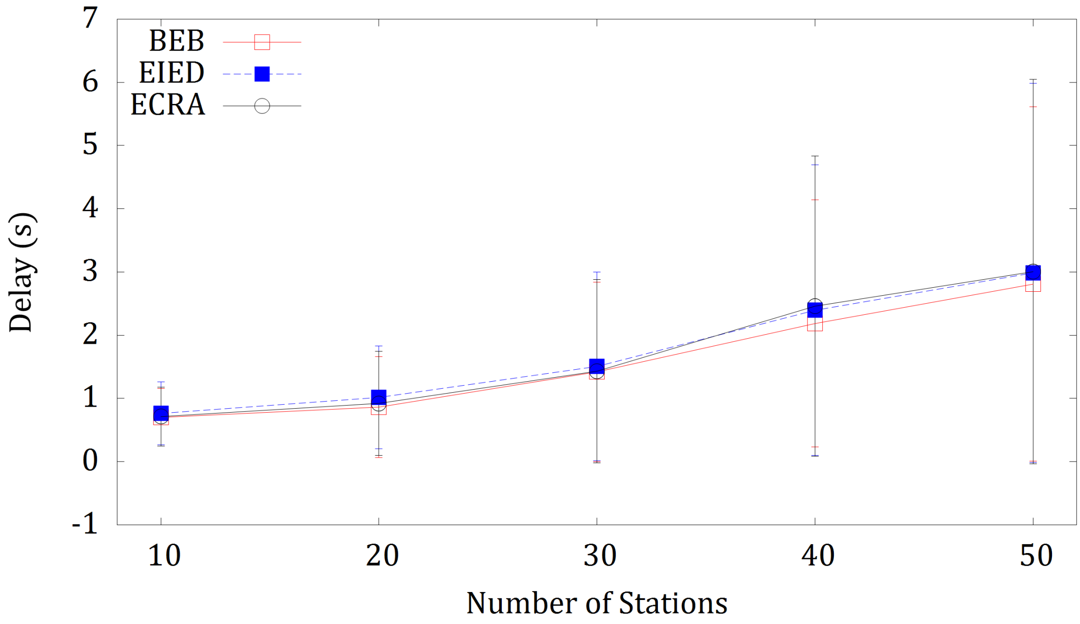

Fig.3.15: Average delay per receiver in mobile environments ± STD

The delay results in the mobile scenario show that BEB, on average, achieves the lowest delay due to its CW reset mechanism. ECRA outperforms EIED in all cases except when the number of stations is 50. On average, ECRA outperforms EIED, which proves that the collisions resolution method is effective since both algorithms employ the same increment/decrement mechanism.

3.5.4 Jitter

The jitter results are shown in Fig.3.16, and the jitter improvement percentages of ECRA and EIED relative to BEB are reported in Table 3.9.

The results show that the proposed algorithm outperforms EIED when the number of stations is low. The proposed algorithm also outperforms BEB when the

Table 3.9: Jitter improvement percentage compared to BEB in mobile environments

	10	20	30	40	50	Average
EIED	-8.6%	-39.3%	10.0%	5.7%	18.0%	-2.8%
ECRA	-0.6%	-1.1%	-11.2%	-17.0%	1.8%	-5.6%

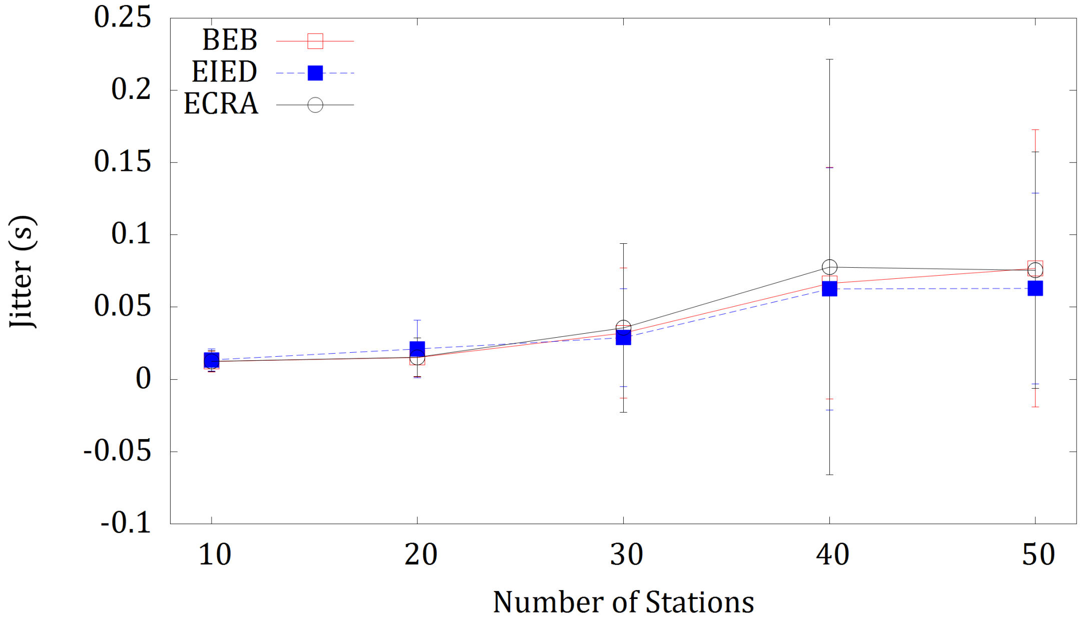

Fig.3.16: Average jitter per receiver in mobile environments ± STD

number of stations reaches 50. The performance of EIED is due to its mechanism retaining a slight variation in CW size among competing stations, thus reducing the variation in delay. ECRA and BEB focus more on improving the channel access time, which results in lower CW values and an increased number of collisions, which affects the jitter.

3.6 Conclusion

In this chapter, we presented our Enhanced Collision Resolution Algorithm, ECRA, and illustrated the operation of ECRA and its collision resolution method. We also implemented an extensive simulation to compare the performance of ECRA to those of BEB and EIED. We presented our simulation environments in detail. We discussed the simulation results in detail and analysed the performance of ECRA compared to that of BEB and EIED.

The simulation results showed that, on average, ECRA outperforms BEB in terms of throughput, fairness, and jitter in fixed environments. For mobile environments, ECRA outperforms BEB in terms of throughput and fairness. The results prove that ECRA improves the performance by employing a collision resolution method to reduce the collision probability without affecting the channel access time. Furthermore, the gradual CW decrease in ECRA enhances fairness among competing stations compared to BEB.

Compared to EIED, on average, ECRA performs better in terms of throughput and delay in fixed environments. For mobile environments, ECRA outperforms EIED in terms of throughput and delay. Regarding fairness, both algorithms performed the same. The throughput and delay results prove that our collision resolution method is effective at improving throughput without affecting delay as EIED does.

Considering the results of ECRA and EIED, and since both algorithms use the same CW increment/decrement method, we can conclude that ECRA improves throughput and fairness without affecting the delay as EIED does. ECRA focuses more on increasing the channel access time by maintaining a small CW range, while EIED acts more greedily and focuses on reducing the collision probability by maintaining a large CW range.

We also noticed the variation in results when comparing fixed environments with mobile environments. In a mobile environment, stations are constantly moving, which might result in a station being out of range, thus increasing the number of dropped packets and decreasing the throughput. The randomness of the mobile scenarios introduces more challenges, as it requires an effective collision resolution method that improves the channel access time and the fairness, throughput, and delay.

Finally, on average, the simulation results show that the throughput performance of ECRA improved by a margin as the number of stations increased. Based on that result, we can project that ECRA will outperform BEB and EIED in terms of throughput in dense networks and future applications such as autonomous cars, where a large number of mobile stations will be constantly transmitting and exchanging data.

Chapter 4

Analytical Model

This chapter presents our analytical model. Our model follows Bianchi's framework [20], using a two-dimensional Markov chain to represent the state transition diagram. In our model, we extend Bianchi's by using a variable collision probability, at each backoff stage, that is dependent on the current CW size rather than using a constant one for all backoff stages. We calculate the collision probability for each backoff stage using the current CW size and the number of active stations.

In Bianchi's model, the collision probability for a given number of stations n is a constant value regardless of the current CW size. This assumption ignores the fact that BEB doubles the CW size to reduce the collision probability; therefore, assuming a constant collision probability regardless of the current CW size will result in an inaccurate throughput analysis.

Using a collision probability that is dependent on the current CW size allows us to account for the station transmission history when calculating the state transition probabilities. To maintain the Markov property that the conditional probability distribution of future states of the process depends on only the present state, not on the sequence of events that preceded it [132, 133], we calculate our collision probability for the final state of each backoff stage.

In Chapter 2, we concluded that the vast majority of the analytical models follow Bianchi's framework with various extensions. We also highlighted that none of the state-of-the-art analytical models uses a collision probability that reflects the effect of the current CW size on the collision probability.

The proposed analytical model is one of the main contributions of this thesis. Our model extends Bianchi's model and presents accurate throughput calculations by taking into account the effect of the previous backoff stage and the current CW range on the collision probability.

In Bianchi's model, assuming that the collision probability is independent of the station transmission history leads to less-accurate estimation of the probability τ that a station transmits in a random timeslot, which results in an inaccurate throughput analysis. For example, in a scenario where a station suffered no previous collisions, the station collision probability will be high compared to its collision probability if it suffered previous collisions. This result is due to the effect of the station's transmission history on its current CW size and therefore its collision probability.

4.1 Proposed Analytical Model

In our proposed analytical model, since we operate under saturated conditions in which each station always has a packet to send, for each backoff stage i, the actual collision probability P_i is calculated as

$$P_i = 1 - \frac{CW_i!}{(CW_i - n)!CW_i^n} \tag{4.1}$$

where $i \in \{0, 1, 2, ..., m\}$, $CW_i = 2^i(CW_{min}+1)-1$, $CW_{min} = 31$, m is the maximum backoff stage, and n is the number of stations.

Furthermore, contrary to Bianchi's model, our model asserts that a BO value of zero is not accepted and that state (0,0), for example, is only accessible from state (0,1). Our analytical model operates under the following assumptions: a fixed number of stations operating under ideal conditions (no hidden stations) and saturated conditions (in which each station always has a packet to transmit).

The remainder of this section is divided into three parts. First, we present our model for BEB and compare it to that of Bianchi. Then, we present our model and τ calculations for EIED and ECRA. We compare the performance of ECRA to those of BEB and EIED with regard to τ, CW average size, channel access time, and the probability of successful transmissions. Finally, we compare saturation throughput and maximum throughput theoretical results of BEB, EIED, and ECRA.

4.1.1 BEB Analysis

The proposed Markov chain model of BEB in Fig.4.1 shows the state transition diagram for the states (i, k), where $i \in \{0,1,...,5\}$, $k \in \{0,...,CW_i\}$, the edges between states represent the transition probability from one state to another, and P_i denotes the collision probability in the backoff stage i. In our model, BEB has 5 stages (m = 5) since $CW_{min} = 31$ and $CW_{max} = 1023$.

To illustrate the process, let the probability that a station is in state (i, k) be $b_{i,k}$. Assuming that a station is in state (i, k), (k >0), at each timeslot, the station will reduce k by a value of one to move to the next state $(i, k-1)$. The station continues reducing k at each timeslot until it is in the state $(i, 0)$, where it can access the channel and attempt to transmit. If a collision occurs, the station moves to a

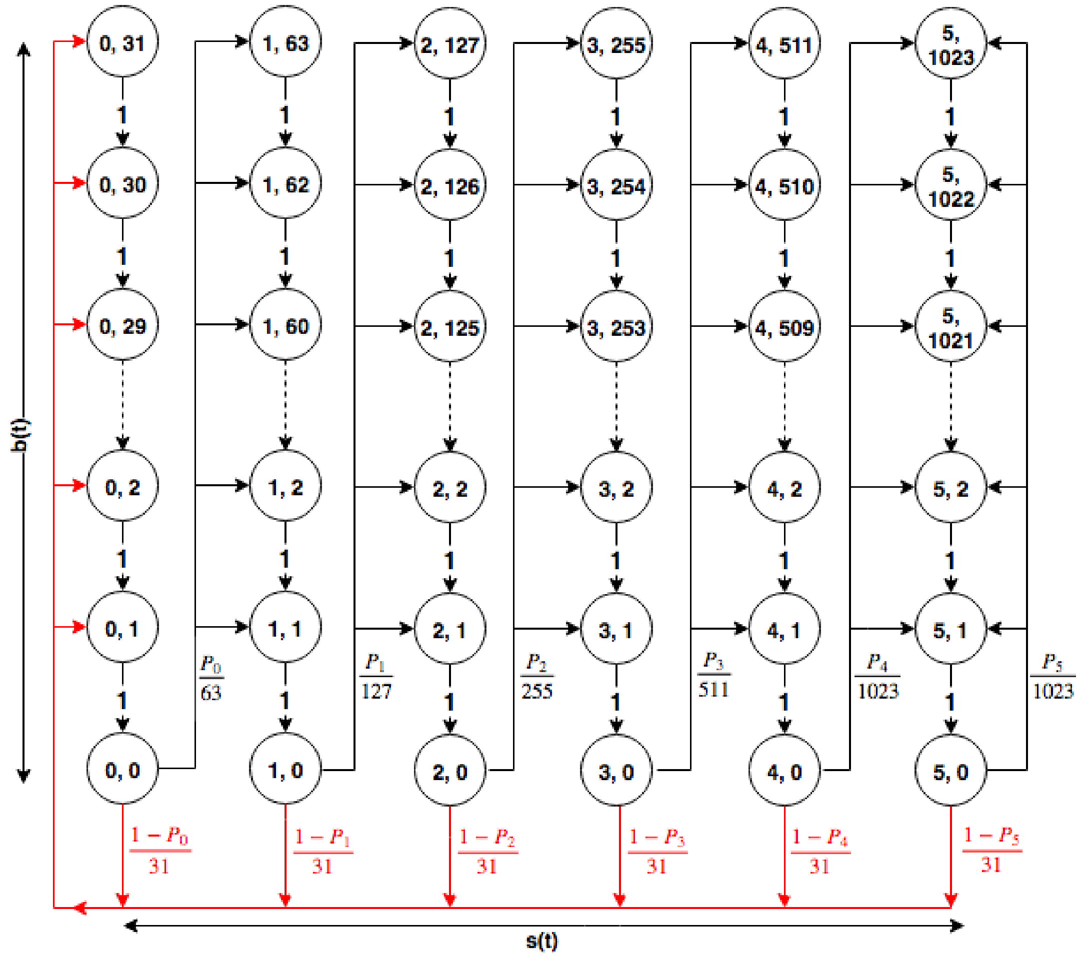

Fig.4.1: Proposed analytical model of BEB

random state in the next backoff stage, and if transmission is successful, the station moves to any random state in the first backoff stage.

In case of a collision, the transition probability from state $(i, 0)$ to any random state in the next backoff stage $(i+1, k)$, $(k > 0)$, is equal to $\frac{P_i}{CW_{i+1}}$. If the transmission is successful, the transition probability from state $(i, 0)$ to any random state in the first backoff stage $(0, k)$, $(k > 0)$, is equal to $\frac{1-P_i}{CW_0}$.

From Fig.4.1, we find that state $(0, 31)$ can be accessed from state $(0, 0)$ conditional on the probability $1/31$ at the beginning of the backoff process; it can also be accessed from all states (where i=0) conditional on their respective probabilities.

Therefore,

$$b_{0,31} = \frac{1}{31}\sum_{j=1}^{5}(1-P_j)b_{j,0} \tag{4.2}$$

The next state $(0,30)$ and all the states in the first backoff stage (where $i=0$) can be accessed similarly to state $(0,31)$. Moreover, since $(0,30)$ can also be accessed from $(0,31)$,

$$b_{0,30} = \frac{2}{31}\sum_{j=1}^{5}(1-P_j)b_{j,0} \tag{4.3}$$

Based on (4.2) and (4.3), we extend our solution to include the remaining states, and we conclude that the transition probability $b_{i,k}$ for any given state (i,k) is

$$b_{i,k} = \frac{CW_i - k}{CW_i}\begin{cases} \sum_{j=0}^{5}(1-P_j)b_{j,0} & i=0 \\ P_{i-1}b_{i-1,0} & 0<i<5 \\ P_{i-1}b_{i-1,0}+P_i b_{i,0} & i=5 \end{cases} \tag{4.4}$$

Since stations will be allowed to transmit only in states where k equals zero (BO $=0$), the probability τ that a station transmits in a random timeslot is

$$\tau = \sum_{i=0}^{5} b_{i,0} \tag{4.5}$$

Since all states where $k=0$ can only be accessed from their respective states where $k=1$, using (4.4), we have

$$b_{1,0} = b_{1,1} = P_0 b_{0,0} \tag{4.6}$$

Similarly,

$$b_{2,0} = b_{2,1} = P_1 b_{1,0} = P_1 P_0 b_{0,0} = X_1 b_{0,0} \tag{4.7}$$

$$b_{3,0} = b_{3,1} = P_2 b_{2,0} = P_2 P_1 P_0 b_{0,0} = X_2 b_{0,0} \tag{4.8}$$

$$b_{4,0} = b_{4,1} = P_3 b_{3,0} = P_3 P_2 P_1 P_0 b_{0,0} = X_3 b_{0,0} \tag{4.9}$$

$$b_{5,0} = b_{5,1} = P_4 b_{4,0} + P_5 b_{5,0} \tag{4.10}$$

$$b_{5,0} = \frac{P_4}{1-P_5} b_{4,0} = \frac{P_4 P_3 P_2 P_1 P_0}{1-P_5} b_{0,0} = X_4 b_{0,0} \tag{4.11}$$

Thus, using (4.5) to (4.9) and (4.11),

$$\sum_{i=0}^{5} b_{i,0} = b_{0,0}\big[1 + P_0 + X_1 + X_2 + X_3 + X_4\big] = X_5 b_{0,0} \tag{4.12}$$

Since in the sum of probabilities of all states equals one, we obtain

$$1 = \sum_{i=0}^{5} b_{i,0} + \sum_{k=1}^{31} b_{0,k} + \sum_{k=1}^{63} b_{1,k} + \sum_{k=1}^{127} b_{2,k} + \sum_{k=1}^{255} b_{3,k} + \sum_{k=1}^{511} b_{4,k} + \sum_{k=1}^{1023} b_{5,k} \tag{4.13}$$

Using (4.4) and (4.6) to (4.11), we obtain

$$\textstyle\sum_{k=1}^{31} b_{0,k} = 16 b_{0,0} \tag{4.14}$$

$$\textstyle\sum_{k=1}^{63} b_{1,k} = 32 P_0 b_{0,0} \tag{4.15}$$

$$\textstyle\sum_{k=1}^{127} b_{2,k} = 64 X_1 b_{0,0} \tag{4.16}$$

$$\textstyle\sum_{k=1}^{255} b_{3,k} = 128 X_2 b_{0,0} \tag{4.17}$$

$$\textstyle\sum_{k=1}^{511} b_{4,k} = 256 X_3 b_{0,0} \tag{4.18}$$

$$\textstyle\sum_{k=1}^{1023} b_{5,k} = 512 X_4 b_{0,0} \tag{4.19}$$

Then, using (4.13) to (4.19), we find

$$b_{0,0} = \frac{1}{\begin{bmatrix} 16 + 32P_0 + 64X_1 + 128X_2 \\ \quad 256X_3 + 512X_4 + X_5 \end{bmatrix}} \tag{4.20}$$

Finally, using (4.12), we have

$$\tau = X_5 b_{0,0} \tag{4.21}$$

4.1.2 EIED Analysis

The proposed Markov chain model of EIED is similar to BEB except that in EIED, there is no sudden reset and CW is decreased gradually. Fig.4.2 shows the state transition diagram for the states (i, k), where $i \in \{0,1,...,5\}$ and $k \in \{0,...,CW_i\}$ (in EIED, $m = 5$ since $CW_{min} = 31$ and $CW_{max} = 1023$).

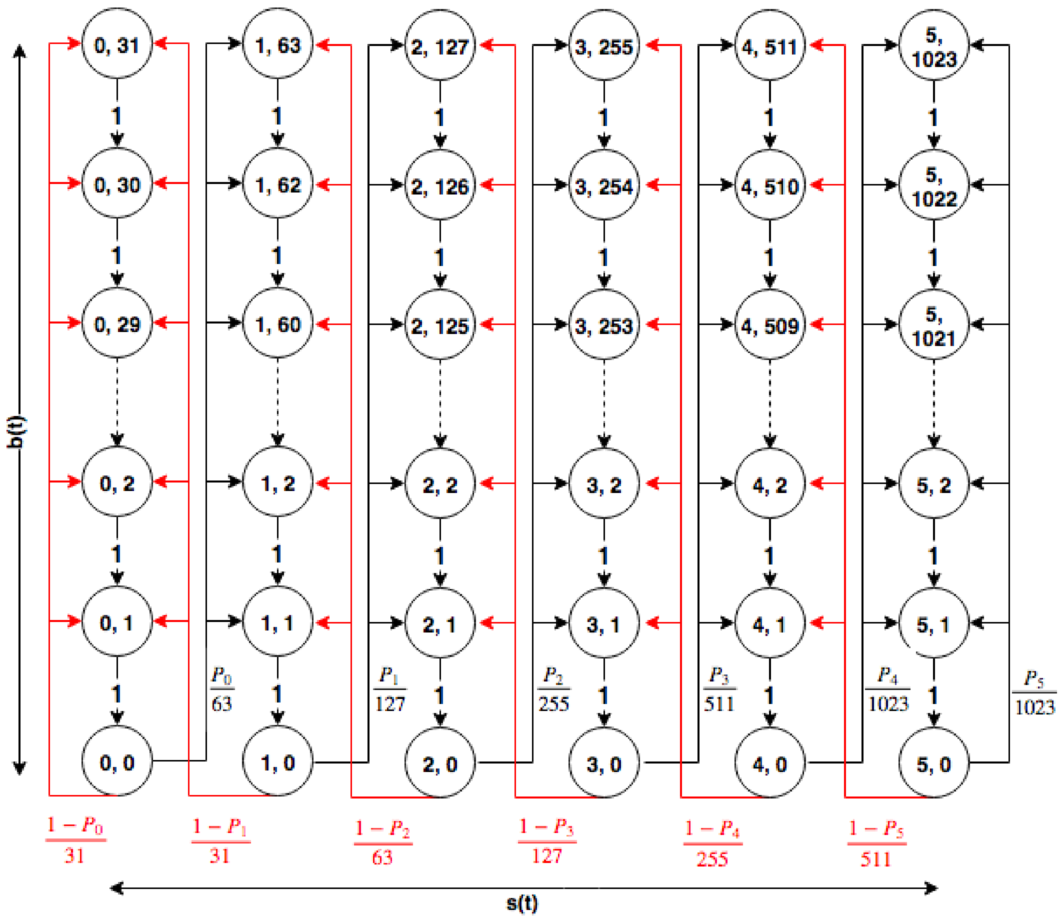

Fig.4.2: Proposed analytical model of EIED

Following the same method we used for BEB, the state transition probability for any given state (i, k) is

$$b_{i,k} = \frac{CW_i - k}{CW_i - 1} \begin{cases} (1-P_i)b_{i,0} + (1-P_{i+1})b_{i+1,0} & i = 0 \\ P_{i-1}b_{i-1,0} + (1-P_{i+1})b_{i+1,0} & 0 < i < 5 \\ P_{i-1}b_{i-1,0} + P_i b_{i,0} & i = 5 \end{cases} \tag{4.22}$$

Since both BEB and EIED have the same number of backoff stages, similar to BEB, τ in EIED is

$$\tau = \sum_{i=0}^{5} b_{i,0} \tag{4.23}$$

Since all states where $k = 0$ can only be accessed from their respective states where $k = 1$, using (4.22), we find

$$b_{5,0} = b_{5,1} = P_4 b_{4,0} + P_5)b_{5,0} = \frac{P_4}{1-P_5} b_{4,0} \tag{4.24}$$

Similarly,

$$b_{4,0} = b_{4,1} = P_3 b_{3,0} + (1-P_5)b_{5,0} = \frac{P_3}{1-P_4} b_{3,0} \tag{4.25}$$

$$b_{3,0} = b_{3,1} = P_2 b_{2,0} + (1-P_4)b_{4,0} = \frac{P_2}{1-P_3} b_{2,0} \tag{4.26}$$

$$b_{2,0} = b_{2,1} = P_1 b_{1,0} + (1-P_3)b_{3,0} = \frac{P_1}{1-P_2} b_{1,0} \tag{4.27}$$

$$b_{1,0} = b_{1,1} = P_2 b_{2,0} + (1-P_2)b_{2,0} = \frac{P_0}{1-P_1} b_{0,0} \tag{4.28}$$

We rewrite (4.24) to (4.28) as

$$b_{1,0} = \frac{P_0}{1-P_1} b_{0,0} = Y_1 b_{0,0} \tag{4.29}$$

$$b_{2,0} = \frac{P_1}{1-P_2} Y_1 b_{0,0} = Y_2 b_{0,0} \tag{4.30}$$

$$b_{3,0} = \frac{P_2}{1-P_3} Y_2 b_{0,0} = Y_3 b_{0,0} \tag{4.31}$$

$$b_{4,0} = \frac{P_3}{1-P_4} Y_3 b_{0,0} = Y_4 b_{0,0} \tag{4.32}$$

$$b_{5,0} = \frac{P_4}{1-P_5} Y_4 b_{0,0} = Y_5 b_{0,0} \tag{4.33}$$

Thus, using (4.29) and (4.33), we have

$$\sum_{i=0}^{5} b_{i,0} = b_{0,0}\big[1 + Y_1 + Y_2 + X_3 + X_4 + Y_5\big] = Y_6 b_{0,0} \tag{4.34}$$

Since the sum of probabilities of all states equals one, we obtain

$$1 = \sum_{i=0}^{5} b_{i,0} + \sum_{k=1}^{31} b_{0,k} + \sum_{k=1}^{63} b_{1,k} + \sum_{k=1}^{127} b_{2,k} + \sum_{k=1}^{255} b_{3,k} + \sum_{k=1}^{511} b_{4,k} + \sum_{k=1}^{1023} b_{5,k} \tag{4.35}$$

Using (4.22) and (4.29) to (4.33), we obtain

$$\textstyle\sum_{k=1}^{31} b_{0,k} = \quad 16 b_{0,0} \tag{4.36}$$

$$\textstyle\sum_{k=1}^{63} b_{1,k} = \quad 32 Y_1 b_{0,0} \tag{4.37}$$

$$\textstyle\sum_{k=1}^{127} b_{2,k} = \quad 64 Y_2 b_{0,0} \tag{4.38}$$

$$\textstyle\sum_{k=1}^{255} b_{3,k} = \quad 128 Y_3 b_{0,0} \tag{4.39}$$

$$\textstyle\sum_{k=1}^{511} b_{4,k} = \quad 256 Y_4 b_{0,0} \tag{4.40}$$

$$\textstyle\sum_{k=1}^{1023} b_{5,k} = \quad 512 Y_5 b_{0,0} \tag{4.41}$$

Then, using (4.35) to (4.41), we find

$$b_{0,0} = \frac{1}{\begin{bmatrix} 16 + 32Y_1 + 64Y_2 + 128Y_3 \\ \qquad 256Y_4 + 512Y_5 + Y_6 \end{bmatrix}} \tag{4.42}$$

Finally, using (4.34), we obtain

$$\tau = Y_6 b_{0,0} \tag{4.43}$$

4.1.3 ECRA Analysis

The proposed Markov chain model for ECRA in Fig.4.3 shows the state transition diagram for the states (i,k) where $i \in \{0,1,...,9\}$ and $k \in \{0,...,CW_i\}$. In ECRA, m = 9 since ECRA includes a collision resolution backoff stage for each normal backoff stage.

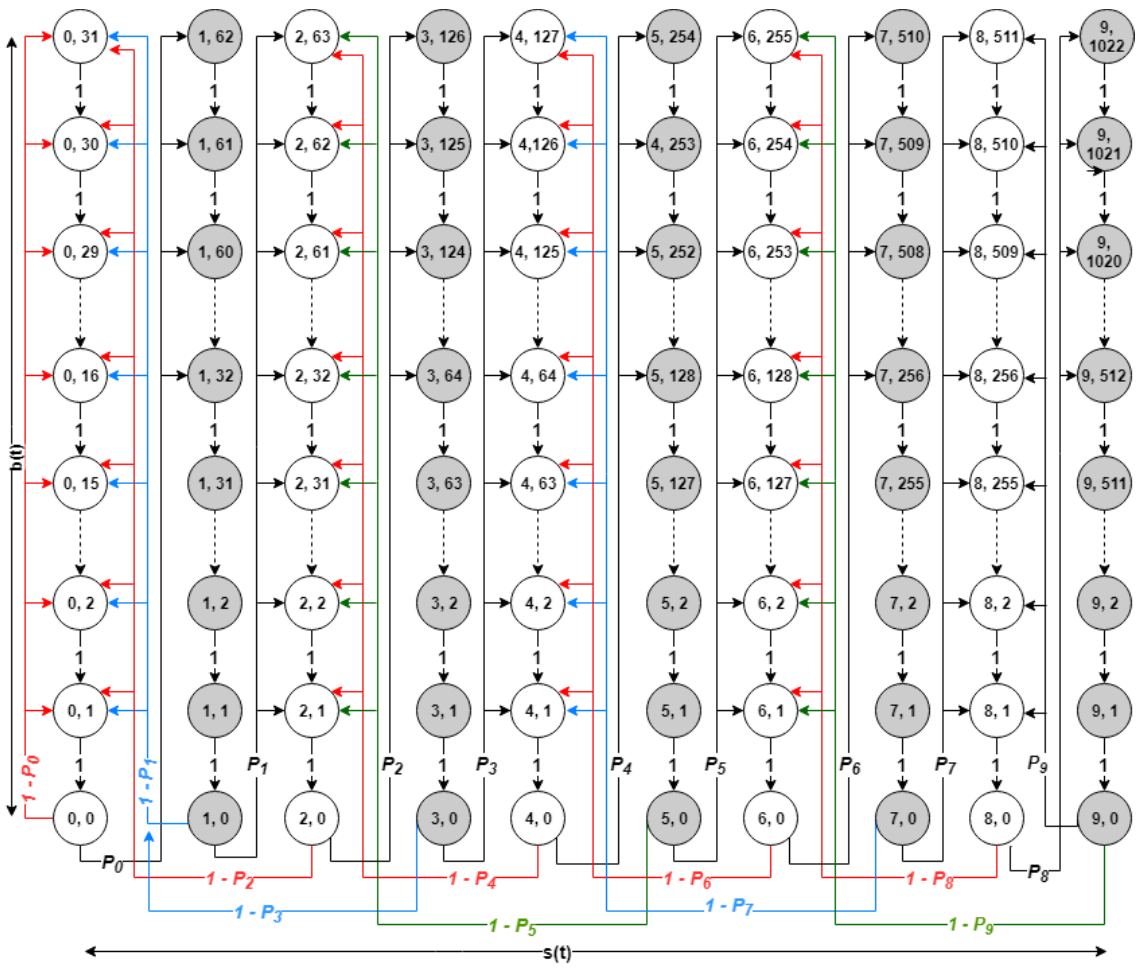

Fig.4.3: Proposed analytical model of ECRA

The proposed analytical model of ECRA contains two different sets of states, which are the five normal backoff states (white) and five collision resolution states (grey). The collision resolution states are the states in which the collision resolution method is used.

Since we have two different sets of states, for the normal backoff stages, we calculate the state probability for any given state (i, k) as

$$b_{i,k} = \frac{CW_i + 1 - k}{CW_i} \begin{cases} \sum_{j=0}^{3}(1 - P_j)b_{j,0} & i = 0 \\ (1 - P_{i+2})b_{i+2,0} + (1 - P_{i+3})b_{i+3,0} + P_{i-1}b_{i-1,0} & 0 < i < 8 \\ P_{i-1}b_{i-1,0} + P_{i+1}b_{i+1,0} & i = 8 \end{cases} \tag{4.44}$$

For the collision resolution backoff stages, we calculate state probability for any given state (i, k) as

$$b_{i,k} = \begin{cases} \frac{2CW_{i-1} - k + 1}{CW_{i-1}} P_{i-1}b_{i-1,0} & k > CW_{i-1} \\ b_{i,k+1} & k <= CW_{i-1} \end{cases} \tag{4.45}$$

For the proposed algorithm, since we have extra backoff stages, we calculate τ as

$$\tau = \sum_{i=0}^{9} b_{i,0} \tag{4.46}$$

Since all stations with $k = 0$ can be accessed from their respective states where $k = 1$, using (4.44) and (4.45), we obtain

$$b_{9,0} = b_{9,1} = P_8 b_{8,0} \tag{4.47}$$

$$b_{8,0} = b_{8,1} = P_9 b_{9,0} + P_7 b_{7,0} = P_8 P_9 b_{8,0} + P_7 b_{7,0} \tag{4.48}$$

We rewrite (4.48) as follows:

$$b_{8,0} = \frac{P_7}{1 - P_8 P_9} b_{7,0} = Z_1 b_{7,0} \tag{4.49}$$

$$b_{7,0} = b_{7,1} = P_6 b_{6,0} \tag{4.50}$$

$$b_{6,0} = b_{6,1} = (1 - P_8) b_{8,0} + (1 - P_9) b_{9,0} + P_5 b_{5,0} \tag{4.51}$$

Let $Z_2 = (1 - P_8) P_6 Z_1$, and $Z_3 = (1 - P_9) P_6 P_8 Z_1$. Then, using (4.47), (4.49) and (4.51), we obtain

$$b_{6,0} = \frac{P_5}{1 - Z_2 - Z_3} b_{5,0} = Z_4 b_{5,0} \tag{4.52}$$

$$b_{5,0} = b_{5,1} = P_4 b_{4,0} \tag{4.53}$$

$$b_{4,0} = b_{4,1} = (1 - P_6) b_{6,0} + (1 - P_7) b_{7,0} + P_3 b_{3,0} \tag{4.54}$$

Let $Z_5 = (1 - P_6) P_4 Z_4$, and $Z_6 = (1 - P_7) P_4 P_6 Z_4$. Then, using (4.50), (4.52) and (4.54), we obtain

$$b_{4,0} = \frac{P_3}{1 - Z_5 - Z_6} b_{3,0} = Z_7 b_{3,0} \tag{4.55}$$

$$b_{3,0} = b_{3,1} = P_2 b_{2,0} \tag{4.56}$$

$$b_{2,0} = b_{2,1} = (1 - P_4) b_{4,0} + (1 - P_5) b_{5,0} + P_1 b_{1,0} \tag{4.57}$$

Let $Z_8 = (1 - P_4) P_2 Z_7$, and $Z_9 = (1 - P_5) P_2 P_4 Z_7$. Then, using (4.53), (4.55) and (4.57), we obtain

$$b_{2,0} = \frac{P_1}{1 - Z_8 - Z_9} b_{1,0} = Z_{10} b_{1,0} \tag{4.58}$$

$$b_{1,0} = b_{1,1} = P_0 b_{0,0} \tag{4.59}$$

Using (4.59), we rewrite (4.47), (4.49), (4.50),(4.52), (4.53), (4.55),(4.56), and

(4.58) as follows:

$$b_{2,0} = \quad P_0 Z_{10} b_{0,0} = Z_{11} b_{0,0} \tag{4.60}$$

$$b_{3,0} = \quad P_0 P_2 Z_{10} b_{0,0} = Z_{12} b_{0,0} \tag{4.61}$$

$$b_{4,0} = \quad P_0 P_2 Z_7 Z_{10} b_{0,0} = Z_{13} b_{0,0} \tag{4.62}$$

$$b_{5,0} = \quad P_0 P_2 P_4 Z_7 Z_{10} b_{0,0} = Z_{14} b_{0,0} \tag{4.63}$$

$$b_{6,0} = \quad P_0 P_2 P_4 Z_4 Z_7 Z_{10} b_{0,0} = Z_{15} b_{0,0} \tag{4.64}$$

$$b_{7,0} = \quad P_0 P_2 P_4 P_6 Z_4 Z_7 Z_{10} b_{0,0} = Z_{16} b_{0,0} \tag{4.65}$$

$$b_{8,0} = \quad P_0 P_2 P_4 P_6 Z_1 Z_4 Z_7 Z_{10} b_{0,0} = Z_{17} b_{0,0} \tag{4.66}$$

$$b_{9,0} = \quad P_0 P_2 P_4 P_6 P_8 Z_1 Z_4 Z_7 Z_{10} b_{0,0} = Z_{18} b_{0,0} \tag{4.67}$$

Using (4.59) through (4.64), we obtain

$$\sum_{i=0}^{9} b_{i,0} = b_{0,0} \big[1 + P_0 + Z_{11} + Z_{12} + Z_{13} + Z_{14} + Z_{15} + Z_{16} + Z_{17} + Z_{18} \big] = Z_{19} b_{0,0} \tag{4.68}$$

Since the sum of probabilities of all states equals one,

$$1 = \sum_{i=0}^{9} b_{i,0} + \sum_{k=1}^{31} b_{0,k} + \sum_{k=1}^{62} b_{1,k} + \sum_{k=1}^{63} b_{2,k} + \sum_{k=1}^{126} b_{3,k} + \sum_{k=1}^{127} b_{4,k} + \sum_{k=1}^{254} b_{5,k} + \sum_{k=1}^{255} b_{6,k} + \sum_{k=1}^{510} b_{7,k} + \sum_{k=1}^{511} b_{8,k} + \sum_{k=1}^{1022} b_{9,k} \tag{4.69}$$

Using (4.44), (4.45) and (4.59) through (4.67), we obtain

$$\sum_{k=1}^{31} b_{0,k} = 16b_{0,0} \tag{4.70}$$

$$\sum_{k=1}^{62} b_{1,k} = 47P_0 b_{0,0} \tag{4.71}$$

$$\sum_{k=1}^{63} b_{2,k} = 32Z_{11} b_{0,0} \tag{4.72}$$

$$\sum_{k=1}^{126} b_{3,k} = 95Z_{12} b_{0,0} \tag{4.73}$$

$$\sum_{k=1}^{127} b_{4,k} = 64Z_{13} b_{0,0} \tag{4.74}$$

$$\sum_{k=1}^{254} b_{5,k} = 191Z_{14} b_{0,0} \tag{4.75}$$

$$\sum_{k=1}^{255} b_{6,k} = 128Z_{15} b_{0,0} \tag{4.76}$$

$$\sum_{k=1}^{510} b_{7,k} = 383Z_{16} b_{0,0} \tag{4.77}$$

$$\sum_{k=1}^{511} b_{8,k} = 256Z_{17} b_{0,0} \tag{4.78}$$

$$\sum_{k=1}^{1022} b_{9,k} = 767Z_{18} b_{0,0} \tag{4.79}$$

Thus, using (4.68) and (4.69), we obtain

$$b_{0,0} = \frac{1}{\left[\begin{array}{r} 16 + 16P_0 + 32Z_{11} + 95Z_{12} + 64Z_{13} + 191Z_{14} + 128Z_{15} \\ + 383Z_{16} + 256Z_{17} + 767Z_{18} + Z_{19} \end{array}\right]} \tag{4.80}$$

Finally, we calculate τ as

$$\tau = Z_{19} b_{0,0} \tag{4.81}$$

4.2 Theoretical Results

In this section, we compare the saturation throughput results for BEB using our model to those of BEB using Bianchi's model. We also compare the saturation and maximum throughput results for ECRA to those of BEB and EIED using our analytical model.

To calculate the saturation throughput, which is defined in [20] as the fraction of time the channel is used to successfully transmit the payload bits, we use [20]

$$S = \frac{\textit{E(Payload transmitted in timeslot)}}{\textit{E(Length of timeslot)}} \tag{4.82}$$

We follow a framework similar to Bianchi's [20, 28], as we analyse the different events that can occur in a random timeslot and the different timeslot lengths based on such events.

We start by finding the probability P_d that the channel is idle. A channel is idle if there is no transmission in a timeslot. Since each station can transmit with probability τ, the probability that no station transmits for n stations, P_d, is

$$P_d = (1 - \tau)^n \tag{4.83}$$

Therefore, the probability P_t that there is at least one transmission in a timeslot is

$$P_t = 1 - P_d \tag{4.84}$$

The probability P_s of having exactly one transmission in a random timeslot given there is at least one transmission in a timeslot is

$$P_s = \frac{n\tau(1 - \tau)^{n-1}}{P_t} \tag{4.85}$$

Since a collision will occur if there is more than one transmission in a timeslot, the probability of collision P_c is the probability of more than one transmission in a timeslot given that there is at least one transmission in a timeslot. Thus,

$$P_c = P_t(1 - P_s) \tag{4.86}$$

The average duration of a timeslot will depend on the following events [20, 28]: a timeslot is empty if there are no transmissions (duration of an empty timeslot = σ), it equals the average time the channel is sensed by a station with successful transmission T_s, and it equals the average time channel is sensed by a station suffering a collision T_c. Fig.4.4, (4.87) and (4.88) show the duration and calculation of T_s and T_c.

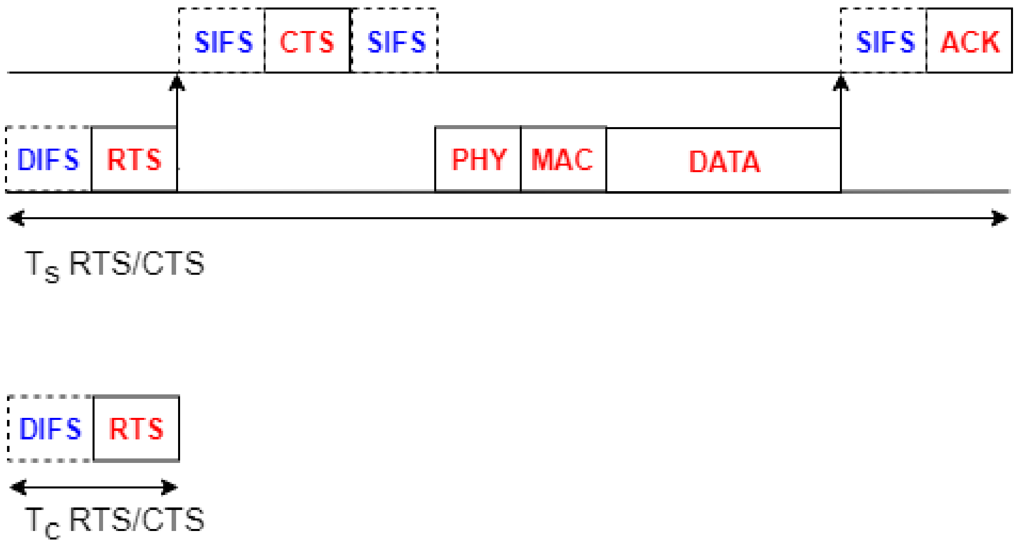

Fig.4.4: The duration of T_s and T_c using RTS/CTS [20]

$$T_c = T_{RTS} + DIFS \tag{4.87}$$

$$\begin{aligned} T_s = {} & DIFS + T_{RTS} + T_{CTS} \\ & + T_{PHY_{PH}} + T_{MAC} + T_{DATA} + 3SIFS + T_{ACK} \end{aligned} \tag{4.88}$$

where:

- T_{DATA}: Time to send payload packet (μs)
- PHY_{PH}: PHY Header + PHY Preamble
- $T_{PHY_{PH}}$: Time to send PHY_{PH}
- T_{MAC}: Time to send MAC header (μs)
- T_{RTS}: Time to send RTS (μs)
- T_{CTS}: Time to send CTS (μs)
- T_{ACK}: Time to send ACK (μs)

Since packets are successfully transmitted if there is exactly one transmission in a timeslot, a timeslot will be empty if there are no transmissions, and a collision will occur if there are more than one transmission in a timeslot, using (4.82), the saturation throughput is calculated as [20]

$$S = \frac{P_t P_s.E(Payload)}{P_d \sigma + P_t P_s T_s + P_c T_c} \tag{4.89}$$

where $E(Payload)$ is the average frame length.

Finally, assuming that each station has a value of τ that reflects a fair and equal channel distribution among n competing stations. This fair and equal channel distribution will result a collision-free environment where every transmission is in fact a successful transmission ($P_s = 1$ and $P_c = 0$). Thus, based on the previous assumptions, the maximum throughput S_{max} is calculated as

$$S_{max} = \frac{P_t.E(P)}{P_d \sigma + P_t T_s} \tag{4.90}$$

To compare the saturation throughput results of BEB using our model to those of BEB using Bianchi's model, we use the same values for the durations of SIFS and

DIFS, in addition to the durations of the RTS, CTS and ACK control frames used in [20], as shown in Table 4.1.

Table 4.1: System parameters used in the analysis [20]

Parameter	Value
$ChannelRate$	1 Mbps
PHY header	128 bits
MAC header	272 bits
ACK	112 bits + PHY header
RTS	160 bits+ PHY header
CTS	112 bits+ PHY
$SIFS$	28 μs
$DIFS$	128 μs
σ	50 μs
$MSDU$	1023 bytes

We start the evaluation by calculating the collision probability P for BEB in both models. In our model, P is calculated using (4.1), while in Bianchi's model, and since we are using the same parameters, we calculate τ using Bianchi's approximate solution [20]:

$$\tau = \frac{\sqrt{\frac{n+2(n-1)(T_c^*-1)}{n}} - 1}{(n-1)(T_c^* - 1)} \approx \frac{1}{n\sqrt{T_c^*/2}} \tag{4.91}$$

where $T_c^* = \frac{T_c}{\sigma}$ and $T_c = 417$ μs [20].

Using the previous formula, we obtained τ values equal to the values obtained in [20]. Since τ is known, we proceed by calculating P as follows [20]:

$$P = 1 - (1 - \tau)^{n-1} \tag{4.92}$$

The results reported in Table 4.2 show that using Bianchi's model, P is constant through all backoff stages, which does not depict the actual situation. For example, operating under saturated conditions with $n = 50$ and CW $= 31$ in the first backoff stage will certainly result in a collision since the number of stations is greater than the CW size.

The decoupling approximation in Bianchi's method neglects the effect of the CW size on the state transition probability and thus will result in an inaccurate throughput analysis. Moreover, the effect of increasing the number of stations on P is almost negligible and does not reflect the actual effect of doubling the CW size on the collision probability.

Table 4.2: Collision probability for BEB in Bianchi's model versus our model

	Our model						**Bianchi's**
Number of stations	P_0	P_1	P_2	P_3	P_4	P_5	P
10	0.804	0.529	0.305	0.164	0.085	0.043	0.364
20	1.000	0.966	0.794	0.535	0.314	0.170	0.376
30	1.000	1.000	0.976	0.831	0.580	0.349	0.380
40	1.000	1.000	0.999	0.960	0.791	0.538	0.381
50	1.000	1.000	1.000	0.994	0.916	0.704	0.383

In our model, using (4.1) to calculate the actual value of P for each backoff stage allows us to calculate the state transition probabilities precisely, as it reflects the current CW size, the transmission history, and the number of active stations. It also allows us to calculate a precise value of τ that reflects the current network status.

The results in Fig.4.5 show that as n approaches 50, the value of τ using Bianchi's model closely approaches its value using our model. The results also show that in both models, the τ values decrease as the number of stations increases; this is mainly due to the increased number of collisions as more stations are trying to access the channel.

In [20], the author stated that the decoupling approximation will result in more accurate results as long as the values of CW and n increase. To further comment on the previous assertion, we calculated τ for a large number of stations. The results in Fig.4.6 show that as n increases the τ values using Bianchi's model closely approaches the actual τ values calculated using our model.

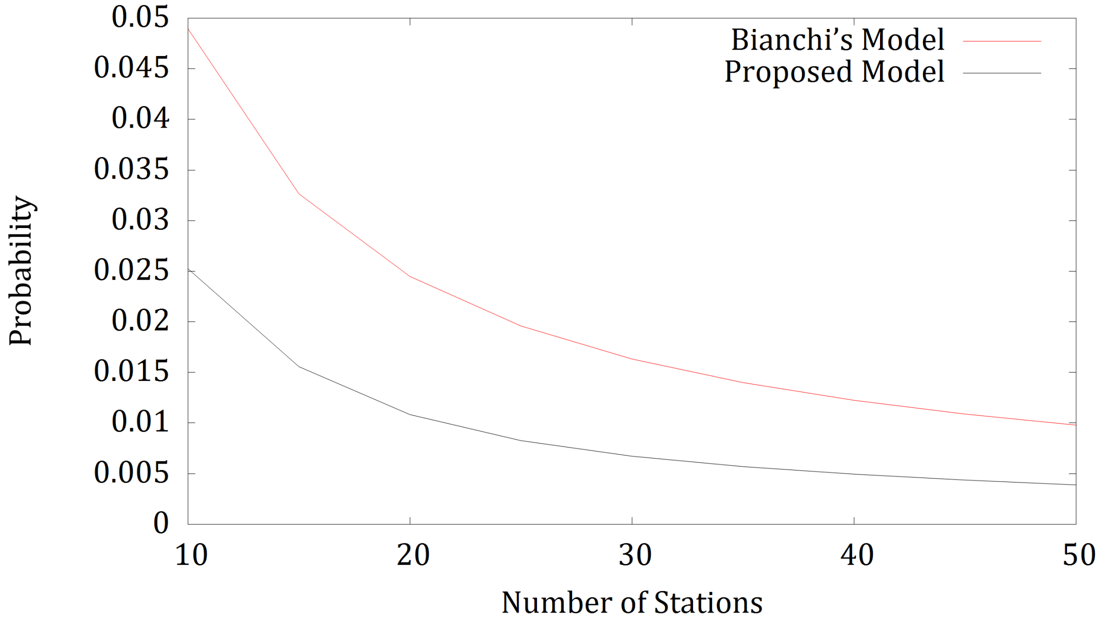

Fig.4.5: Probability that a station transmits in a random timeslot as a function of the number of stations

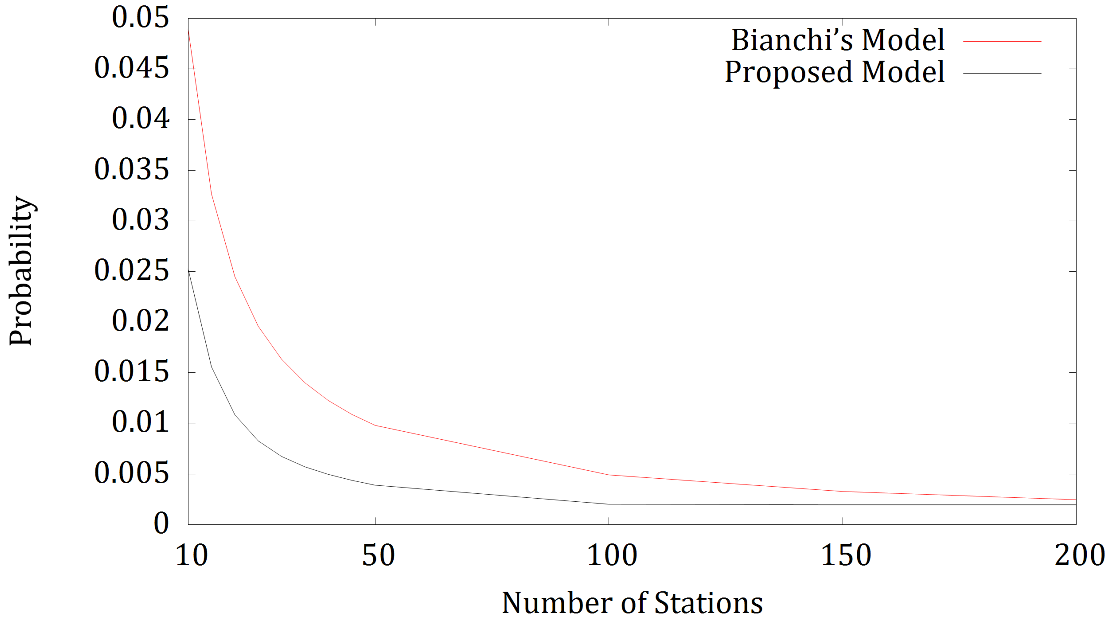

Fig.4.6: Probability that a station transmits in a random timeslot as a function of the number of stations

Fig.4.7 shows the probability that the channel is idle, P_d, in Bianchi's model versus our model. Our model clearly reflects the effect of increasing the number of stations on the channel access time: the channel access time decreases as n becomes larger due to the increased number of collisions. In Bianchi's model, the channel access time is less affected, compared to our model, as n increases, this is mainly due to the decoupling approximation used in Bianchi's model. In our model, calculating the actual values of P allows our model to calculate the actual value of P_d.

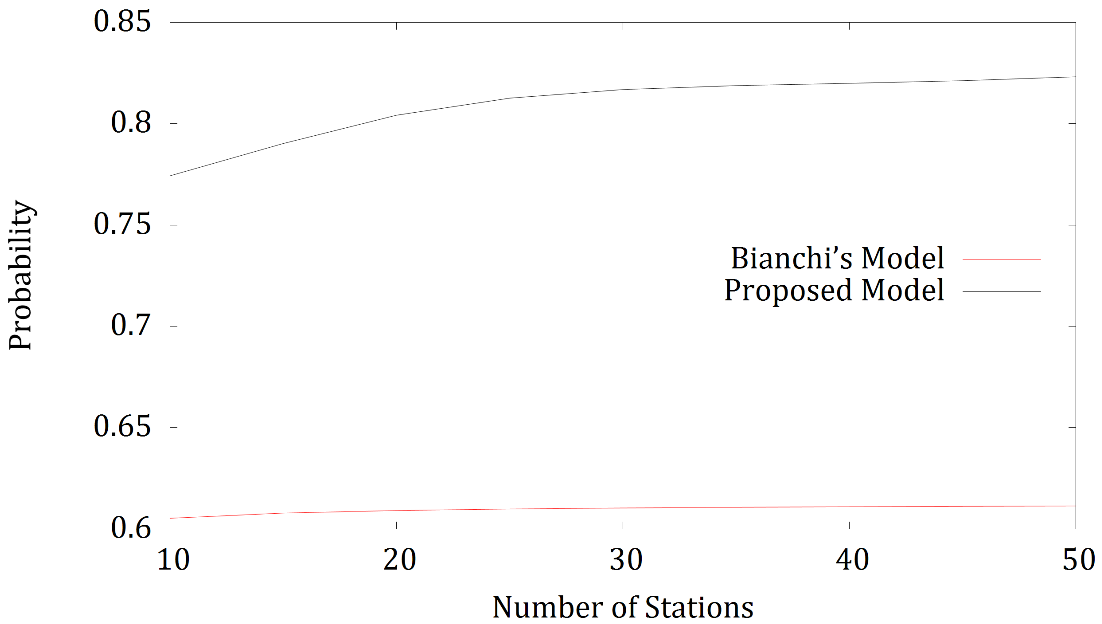

Fig.4.7: Probability that the channel is idle as a function of the number of stations

A similar observation can be made based on Fig.4.8, as our model clearly reflects the effect of increasing n on the transmission probability. As n increases, more collisions will occur, thus increasing the CW size, which results in less channel access time and therefore fewer transmissions. Compared to our model, the effect of increasing the number of active stations in Bianchi's model is unnoticeable.

Fig.4.9 shows that in Bianchi's model, increasing n has a mild effect on the collision probability compared to our model and to actual BEB performance in several research papers [19–23].

The figure also shows that the collision probability decreases as n increases due to the the fact that stations are approaching CW_{max}, which will reduce the collision probability. In Bianchi's model, using a constant value of P reduces the model

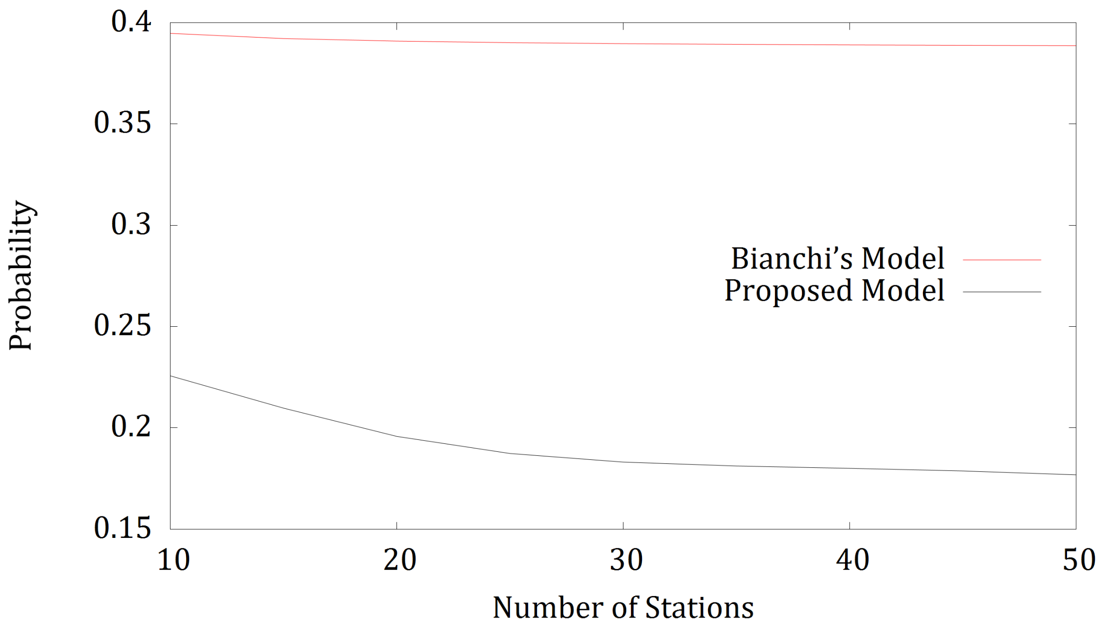

Fig.4.8: Probability of transmission as a function of the number of stations

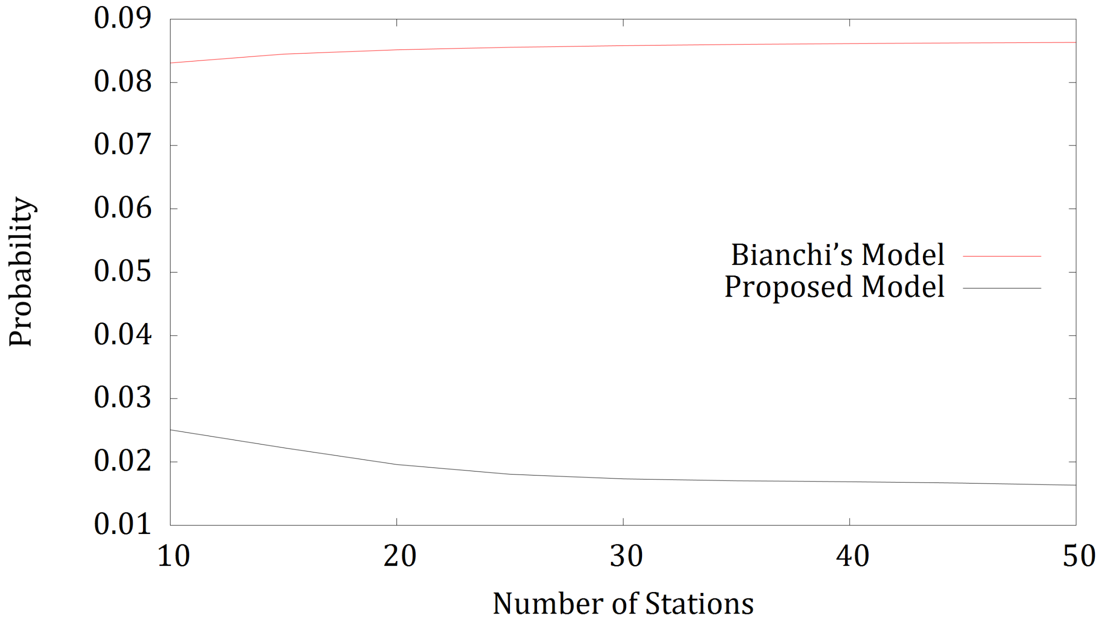

Fig.4.9: Probability of collision as a function of the number of stations

accuracy, as it does not reflect the effect of the size of CW on reducing the collision probability.

Fig.4.10 shows the probability of successful transmission. As both n and CW increase, stations will have less channel access time and will spend more time sensing the channel rather than accessing it, thus reducing the probability of successful transmission. The decoupling approximation in Bianchi's model results in a slight effect of n on the probability of successful transmission compared to our model.

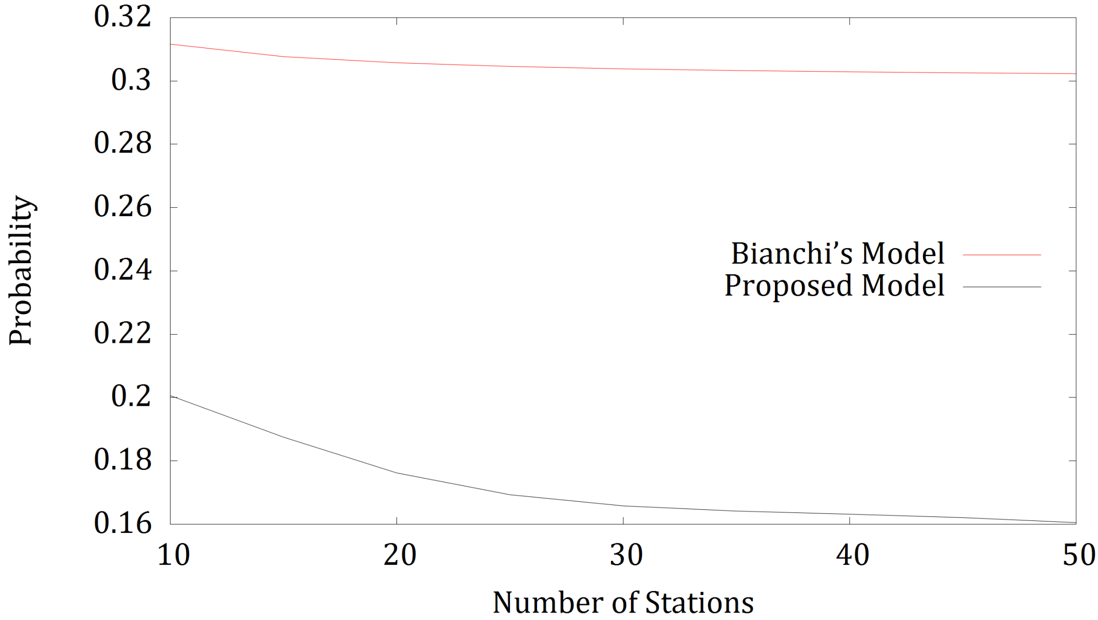

Fig.4.10: Probability of successful transmission as a function of the number of stations

As we stated earlier, the decoupling approximation in Bianchi's model [20] leads to inaccurate throughput analysis because it neglects the effect of the station transmission history on the collision probability. The saturation throughput results in Fig.4.11 show that compared to our model, the saturation throughput in Bianchi's model slowly decreases as the number of stations increases.

Bianchi's model's depiction of the performance of BEB in Fig.4.11 contradicts the actual performance of BEB in several studies [19–23]. In these studies it was established that BEB performance degrades heavily as the number of stations increases. Actually, the performance of BEB in dense networks is the main motive for backoff research.

Fig.4.11 shows that the throughput, according to Bianchi's model, slowly decreases as the number of active stations increases. However, several studies con-

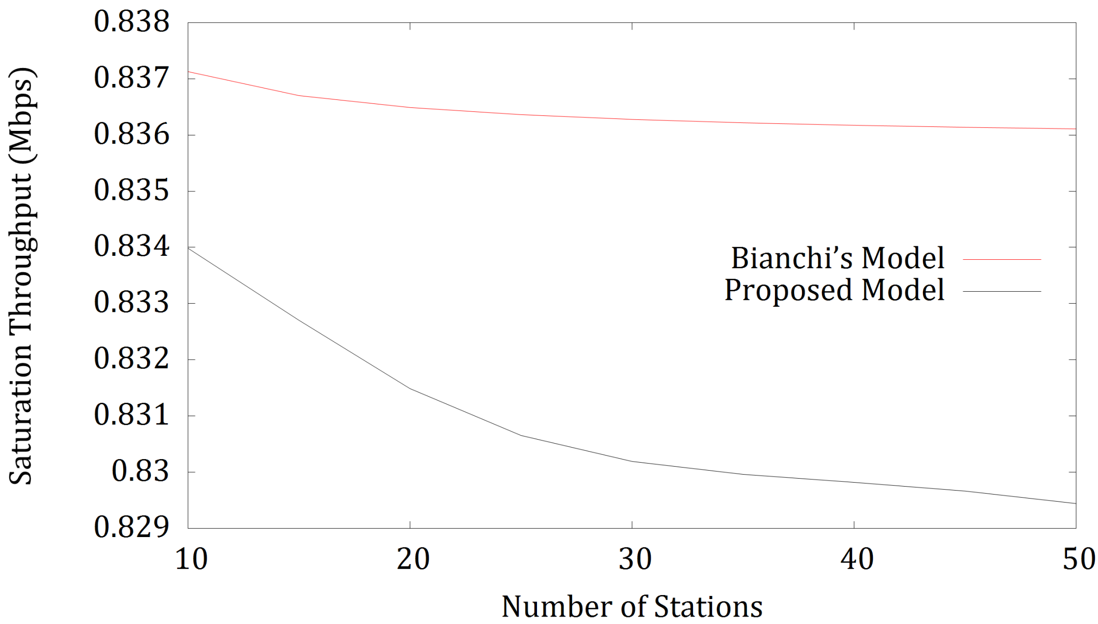

Fig.4.11: Saturation throughput as a function of the number of active stations

cluded that the performance of BEB in terms of throughput rapidly degrades as the number of active stations increases. The saturation throughput analysis using our model depicts the actual behaviour of BEB in our simulation and in many other studies [19–23], as it is calculated using precise collision probability values, and highlights the effect of increasing the number of stations on its performance.

To analyse the throughput performance of ECRA versus those of BEB and EIED using our analytical model, we use the standard values for SIFS and DIFS duration, as well as the durations of the RTS, CTS and ACK control frames [5]. We assume that all packets have the same size of 802.11 MAC Service Data Unit (MSDU) with a channel bit rate of 11 Mbps, as reported in Table 4.3.

Following Bianchi's procedure [20], we start our analysis by studying the behaviour of a single station. We notice in Fig.4.12 that ECRA increases τ compared to BEB and EIED, which is due to the collision resolution method employed in ECRA and the fact that it does not immediately increase the CW size upon collisions.

Table 4.3: Theoretical analysis parameters

Parameter	Value
$ChannelRate$	11 Mbps
$T_{PHY_{PH}}$	192 μs
MAC header	34 octets
ACK	14 octets + PHY_{PH}
RTS	20 octets + PHY_{PH}
CTS	14 octets + PHY_{PH}
$SIFS$	10 μs
$DIFS$	50 μs
σ	20 μs
$MSDU$	2304 bytes

Using the collision method in ECRA increases the channel access time by maintaining lower CW values compared to BEB and EIED. To reduce the collision probability, BEB and EIED instantly increase the CW size upon collision. The instant increase of the CW size reduces the channel access time since stations will spend more time sensing the channel rather than accessing it.

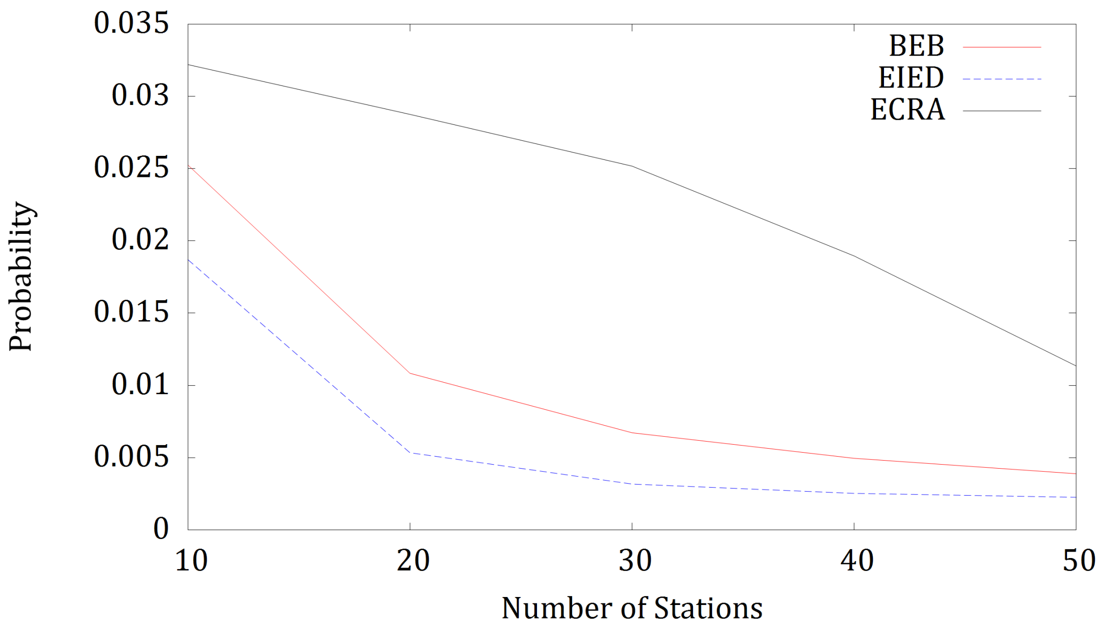

Fig.4.12: Probability that a station transmits in a random timeslot as a function of the number of stations

To prove the effectiveness of our collision resolution method at reducing the average CW size, we calculate the average CW size for a station using the probability that a station is in a backoff stage and the average CW size in that stage. Then, we calculate the average CW size in all the backoff stages. The average CW size results in Fig.4.13 show that ECRA maintains a very low average CW compared to those of BEB and EIED.

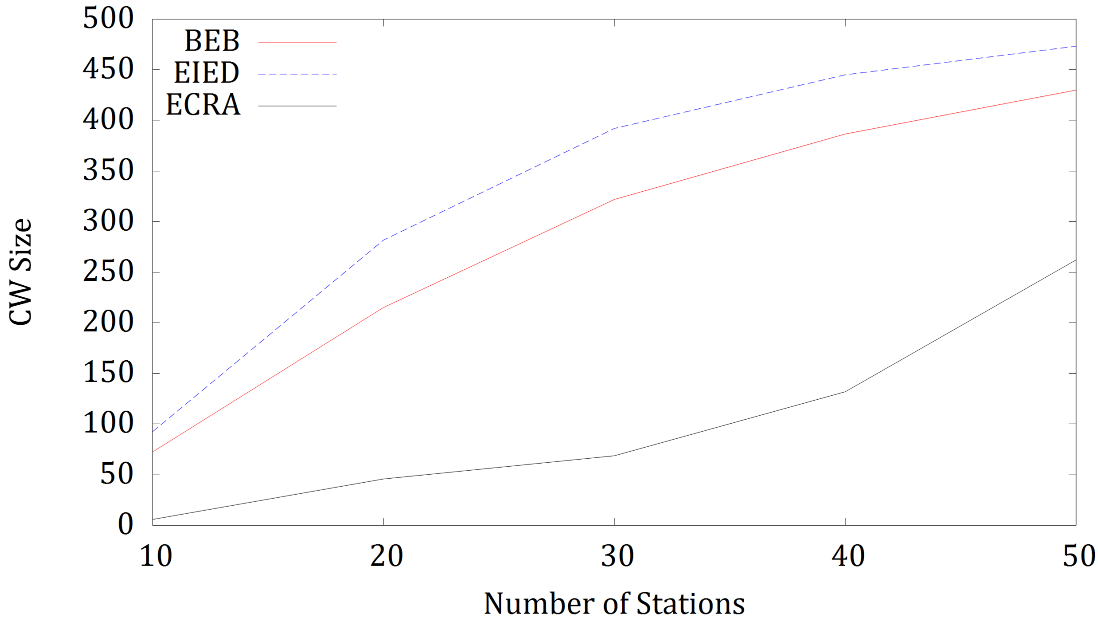

Fig.4.13: Average CW size

Since ECRA successfully increased τ and decreased the average CW size for a single station, it should reduce the probability of an idle channel. The results in Fig.4.14 shows that ECRA increases the channel access time compared to EIED and BEB by keeping the CW size relatively small. The results reflect the behaviour of the algorithm in terms of the compromise between reducing the collision probability and increasing the channel access time. The results also show the effect of increasing n on ECRA as the channel access time is reduced when $n = 50$ due to the high number of collisions.

EIED is an example of backoff algorithms that focus on reducing the collision probability, while BEB focuses on improving the channel access time. ECRA outperforms the two algorithms by focusing on increasing the channel access time and uses the collision resolution method to solve the resulting collisions.

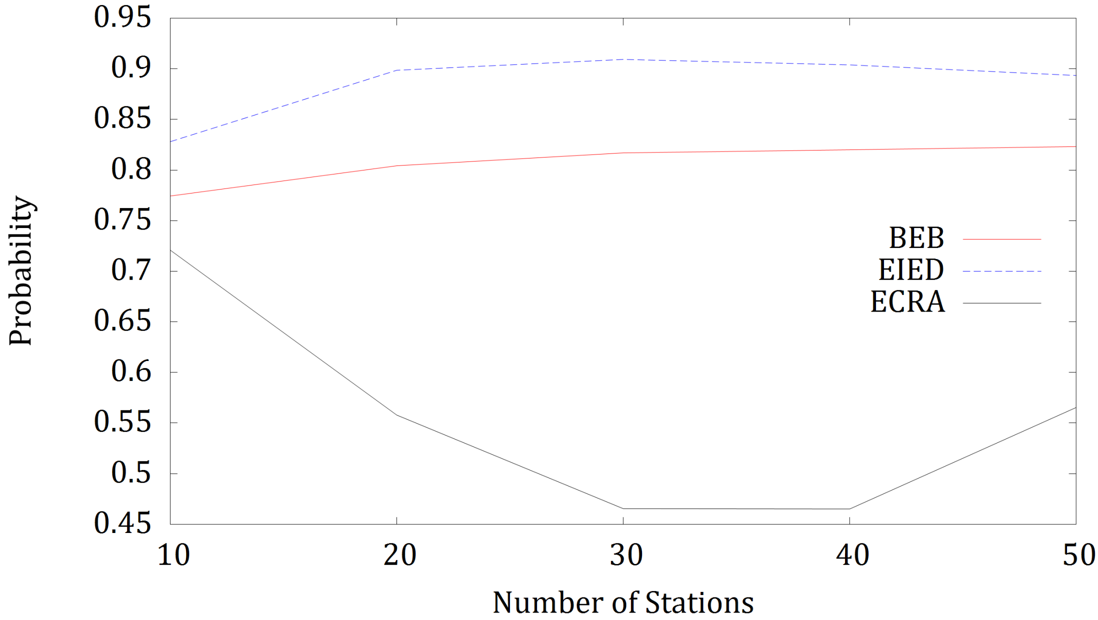

Fig.4.14: Probability that the channel is idle as a function of the number of stations

Fig.4.15 shows that ECRA increases the probability that a station transmits compared to BEB and EIED. Increasing the transmission probability is a direct effect of increasing τ and increasing the channel access time.

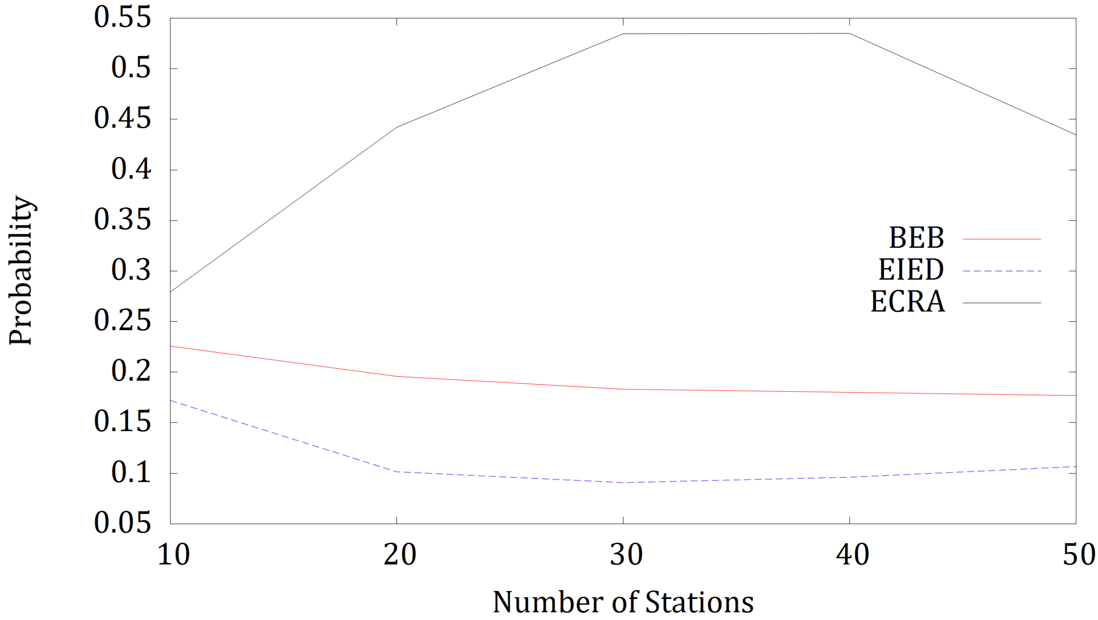

Fig.4.15: Probability of transmission as a function of the number of stations

The results also highlight an important feature of our algorithm: ECRA increases the transmission probability even if the number of stations increases since it separates colliding stations in contention of their own, thus allowing other stations more channel access.

The collision resolution process in ECRA aims to solve collisions once they occur by separating colliding stations from other stations to reduce the collision probability in retransmission. ECRA guarantees that in order for a collision to occur in retransmission, the colliding stations must pick the same value from $[0, CW_{max} - 1]$. It also separates the colliding stations from other stations by adding the previous CW value to the BO. This feature enables ECRA to operate better than BEB and EIED in dense networks, and it proves the effectiveness of our collision resolution method.

The results in Fig.4.16 show that ECRA suffers more collisions compared to BEB and EIED, which is mainly due to ECRA's preference for increasing the channel access time by maintaining the same CW size upon collisions. ECRA focuses more on increasing the channel access and solving collisions using the collision resolution method.

The results also show that EIED suffers the fewest collisions, as it prefers to reduce the collision probability relative to increasing the channel access time. This result supports our previous conclusion regarding the nature of the backoff algorithms.

Fig.4.17 shows that ECRA has a higher probability of successful transmission compared to BEB and EIED. Despite the high number of collisions suffered in ECRA, the algorithm increases the number of successful transmissions, which proves the effectiveness of our collision resolution method. The results also show that ECRA is lightly affected as the number of stations increases compared to BEB and EIED, which highlights its ability to operate in dense networks compared to BEB and

EIED.

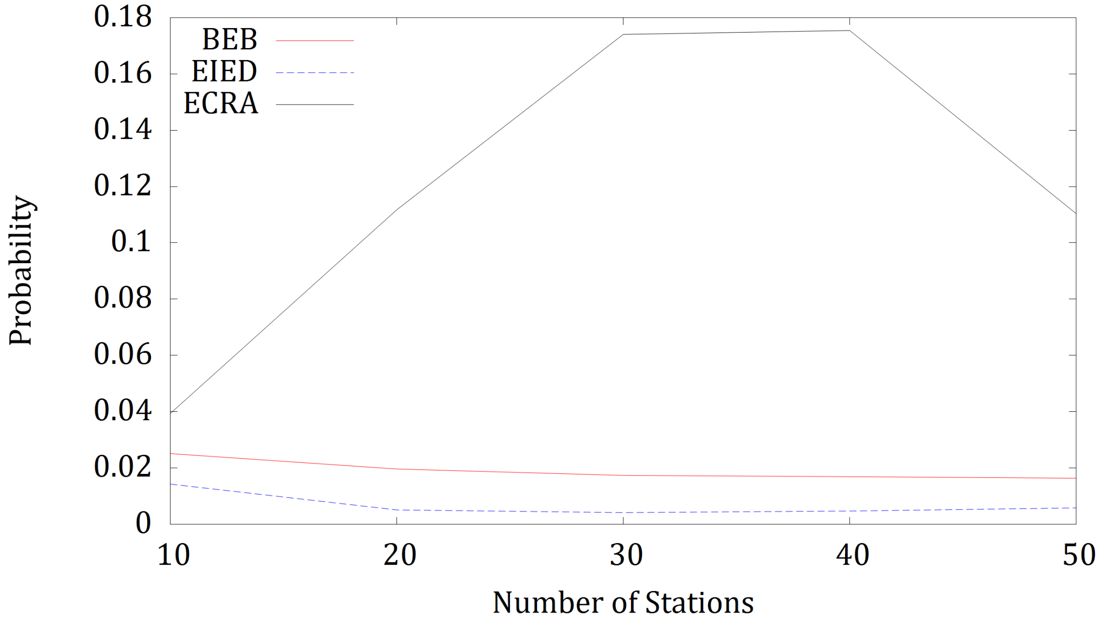

Fig.4.16: Probability of collision as a function of the number of stations

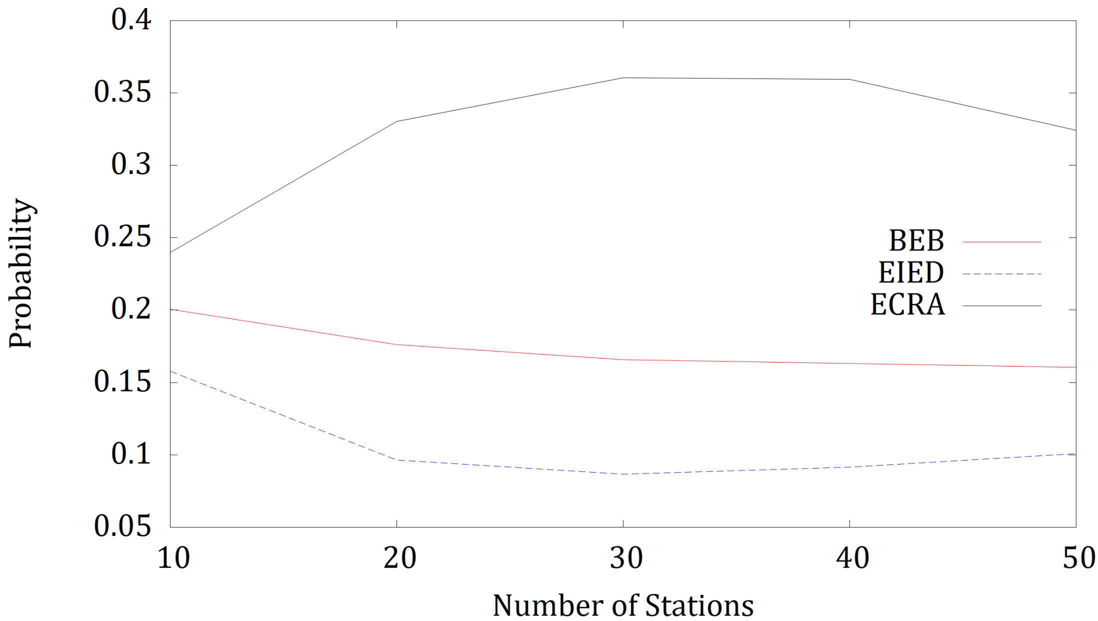

Fig.4.17: Probability of successful transmission as a function of the number of stations

The results also show that the performance of ECRA degrades as n reaches 50 since the increased number of collisions will affect the probability of successful transmission. Despite this effect, ECRA still performs better compared to BEB and

EIED.

The results also show that in ECRA, as the number of stations and number of collisions increase, the collision resolution method operates effectively in solving collisions without affecting the channel access time, thus providing stations with more transmission time.

Finally, by increasing channel access, increasing the number of successful transmissions, and reducing the average CW size for each station, ECRA outperforms BEB and EIED in terms of saturation and maximum throughput. Fig.4.18 and Fig. 4.19 show the saturation and maximum throughput results for ECRA, BEB, and EIED.

The results in Fig.4.18 show that ECRA achieves higher saturation throughput compared to BEB and EIED. The results also show that the collision resolution method in ECRA is effective because it allows ECRA to maintain its performance despite the increased number of stations. The results prove that ECRA is more suitable to operate under dense conditions than BEB and EIED.

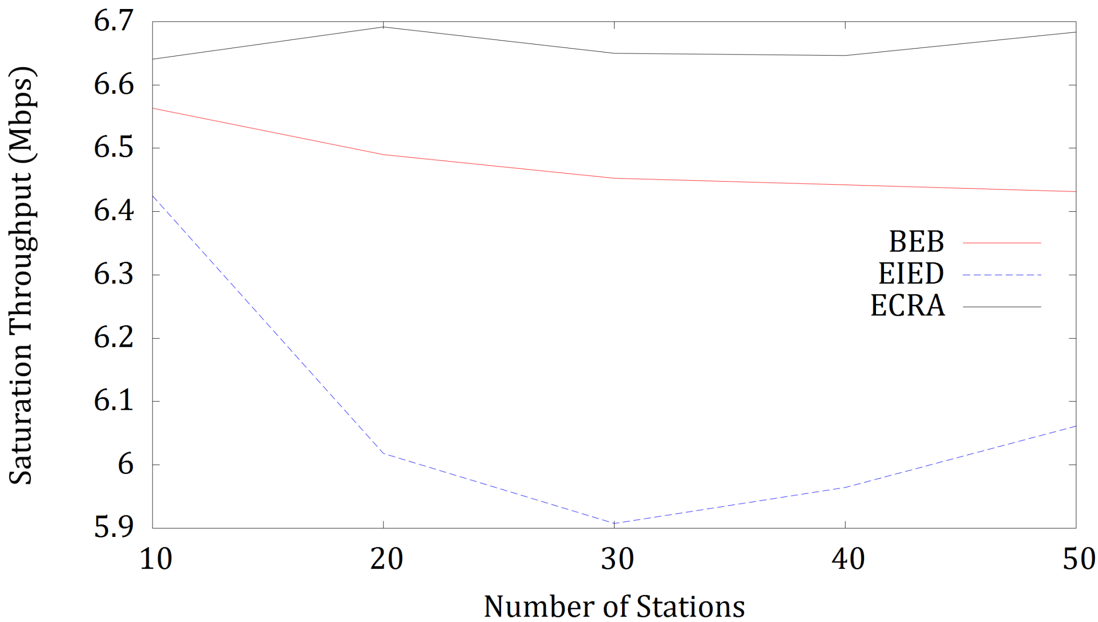

Fig.4.18: Saturation throughput as a function of the number of active stations

The difference between the throughput results in the simulation in Fig.3.9 and the theoretical results in Fig.4.18 is due to the environment settings. In the theoretical analysis, we calculate the throughput assuming saturated conditions and ideal channel conditions.

In the simulation, we created a variety of scenarios to cover different network conditions. Because of the stated differences, we cannot compare the simulation results to the theoretical results because the theoretical analysis operates under ideal conditions (no hidden station problem, no packet loss, and no packet error) which can not be implemented in simulation.

However, in general, both the theoretical analysis results and the simulation results show that ECRA and BEB outperform EIED in terms of throughput, and they also show that ECRA outperforms BEB. Both the simulation and theoretical analysis results show that the throughput decreases as the number of stations increases and that ECRA and EIED cope better with an increasing number of active stations than BEB.

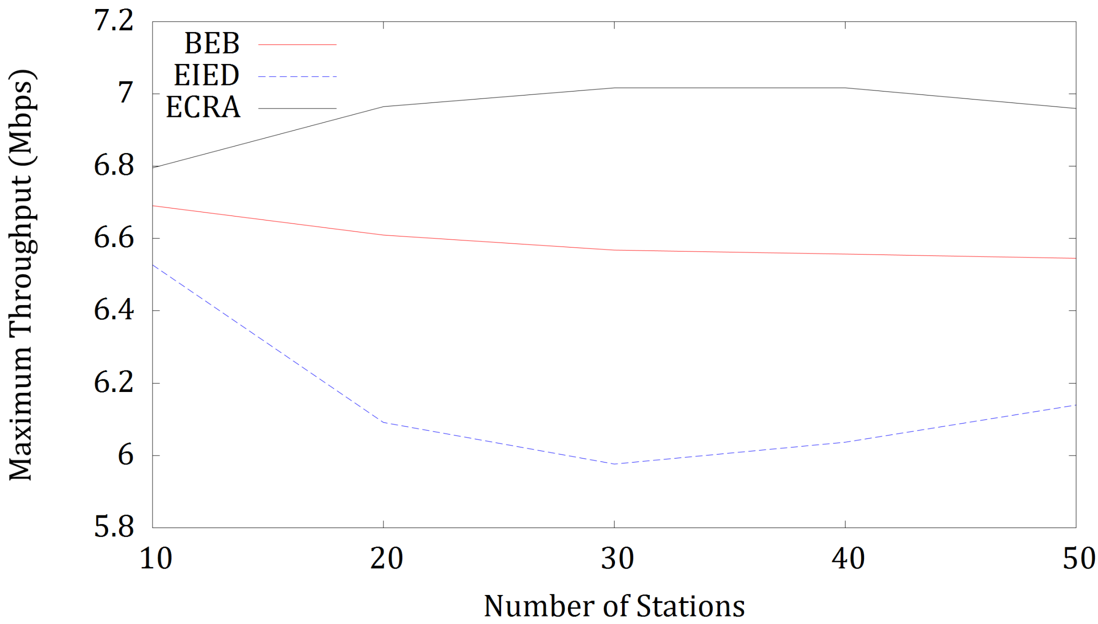

Fig.4.19: Maximum throughput as a function of the number of active stations

The results in Fig.4.19 show that ECRA outperforms BEB and EIED in terms of maximum throughput. ECRA maintains its performance as the number of active stations increases, and it exhibits similar behaviour in terms of its saturation throughput performance. The results also show that BEB outperforms EIED, this is mainly due to the ability of BEB to increase the channel access time compared to EIED.

4.3 Conclusion

In this chapter, we presented our analytical model, and we highlighted the main contributions of our model. The main idea of our model is using a collision probability that is dependent on the station transmission history. We believe that using an accurate probability allows us to calculate a precise value for τ, which yields an accurate saturation and maximum throughput analysis. Contrary to Bianchi's model and the vast majority of the existing IEEE 802.11 analytical models, our model does not operate under the decoupling approximation.

We compared the saturation throughput of BEB using our model to that of BEB using Bianchi's model. We concluded that our model provides an accurate depiction of the BEB throughput behaviour under real network conditions. We also concluded that compared to Bianchi's model, our model reflects the actual effect of the number of active stations on the throughput analysis.

We also compared the performance of our algorithm in terms of the average CW size, transmission probability, collision probability, channel access time, successful transmission probability, and saturation and maximum throughput to those of BEB and EIED using our model. We concluded that ECRA outperforms both EIED and BEB in terms of saturation throughput and maximum throughput. We also concluded that ECRA is more effective than BEB and EIED, especially in dense networks, as its performance was not affected by increasing the number of active stations.

The differences in throughput results between the simulations and theoretical analysis are due to the following factors: the analytical models operate under ideal network conditions and saturated conditions, which are rarely applicable in simulations. Moreover, the simulation results show the throughput as an average per receiver, while the theoretical analysis shows throughput results for the system. Despite the different network conditions, both the theoretical and simulation throughput results show that, on average, ECRA outperforms both BEB and EIED. The results also show that ECRA and EIED address the increased number of stations in a better way than BEB.

Chapter 5

Conclusion and Future Work

This thesis proposed a backoff algorithm that uses a collision resolution method to solve collisions rather than instantly increasing the CW size. This thesis also proposed a Markov chain model to theoretically evaluate the performance of the proposed algorithm, BEB ,and EIED.

Chapter 1 introduced the research problem, the motivation, our research methodology, and our contributions. We highlighted the main limitations of BEB and state-of-the-art backoff algorithms. We also established a set of guidelines for designing a backoff algorithm.

Chapter 2 presented the background and a review of the literature related to the contributions of this thesis. We presented a brief introduction of wireless networks, IEEE 802.11, and DCF. We provided a comprehensive review of state-of-the-art backoff algorithms. We also presented the state of the art in IEEE802.11 analytical modelling.

Chapter 3 presented ECRA. We provided an extensive description of ECRA. Then, we presented the simulation settings and the performance metrics of our simulation. The simulation results took into consideration many scenarios, including fixed and mobile environments. We presented results showing how the performance of ECRA compares to those of BEB and EIED.

Chapter 4 presented our analytical model. We compared our model to Bianchi's model, which is the most commonly applied model in IEEE 802.11 DCF analysis. We implemented ECRA, BEB, and EIED using our analytical model; then, we compared the saturation and maximum throughput performance of ECRA to those of BEB and EIED.

5.1 Thesis Contribution

This thesis contributed to the body of research regarding backoff algorithms and their analytical modelling.

In Chapter 2, we concluded that increasing the CW upon collisions is not justified since a collision is assumed based on the absence of CTS or ACK frames, which can be attributed to other factors in WANETs. Moreover, the CW increase becomes ineffective as the number of active stations increases since its reduction of the collision probability becomes insignificant. We also concluded that increasing the CW size will reduce the channel access time since stations will be busy sensing the channel rather than accessing it.

To overcome the shortcomings of BEB and the state-of-the-art algorithms highlighted in Chapter 2, we proposed our Enhanced Collision Resolution Algorithm (ECRA). Our algorithm uses a collision resolution method to solve collisions rather than instantly increasing the CW size. Our algorithm reduces the collision probability without increasing the CW size; thus, it increases the channel access time and reduces the number of collisions at the same time.

We implemented ECRA over exponential increment/exponential decrement to maintain fairness among competing stations and avoid the negative effects of the CW reset employed by BEB. In ECRA, colliding stations were separated in contention of their own to avoid any collisions with other stations and thus improve the collision resolution method.

In Chapter 3, the simulation results showed that, on average, ECRA outperforms BEB in terms of throughput, fairness, and jitter in fixed environments. For mobile environments, ECRA outperforms BEB in terms of throughput and fairness. The results prove that ECRA improves the performance of DCF by employing a collision resolution method to reduce the collision probability without affecting channel access time. Furthermore, the gradual CW decrease in ECRA enhances fairness among competing stations compared to BEB.

The simulation results also indicated that the performance of ECRA improved in terms of throughout as the number of active stations increased. This result shows that ECRA was able to solve the shortcomings of BEB for dense networks.

The simulation results also showed that the collision resolution method in ECRA was effective, as it was the reason for improving fairness and throughput by reducing the number of collisions and increasing the channel access time.

Compared to EIED, on average, ECRA performs better in terms of throughput and delay in fixed environments. For mobile environments, ECRA outperforms EIED in terms of throughput and delay. Regarding fairness, both algorithms performed the same. The throughput and delay results prove that our collision resolution method is effective at improving throughput without affecting delay as EIED does.

The simulation results showed that ECRA is effective at reducing collisions since both ECRA and EIED use the same exponential increment/decrement mechanism, yet using the collision resolution method, ECRA was able to outperform EIED in terms of throughput without affecting the delay.

We conclude that although the EIED process of reducing CW gradually upon successful transmission and increasing the CW size upon collisions improves the throughput and fairness, it will negatively affect delay. In contrast to EIED, using the collision resolution method in ECRA improved the throughput and fairness without having the same negative effect on delay.

The main limitation of our algorithm is the increased jitter compared to EIED and increased delay compared to BEB. The main reason for such limitations is the process of separating the colliding stations in contention of their own by adding the current CW size to their BO. We highlighted this limitation as a focus for our future work, and we aim to provide a more effective solution to improve the performance of our algorithm.

The limitations and shortcomings of the state of the art in IEEE 802.11 analytical modelling, presented in Chapter 2, led us to develop an accurate Markov chain analytical model to analyse the throughput of IEEE 802.11 DCF under saturated conditions. Our model extends existing models by using a collision probability that depends on the station transmission history. This approach allows our model to calculate a precise value of the probability a station transmits in a random timeslot, which will result in an accurate throughput analysis.

We evaluated the performance of BEB using our model compared to that of BEB using Bianchi's. We proved that BEB analysis, using our model, provided a more accurate BEB behaviour that reflects its behaviour in WANETs. BEB throughput analysis using our model showed that our model reflects the effect of increasing the number of stations on throughput more accurately than Bianchi's. Most of the existing IEEE 802.11 analytical models, similar to Bianchi's, operate under the decoupling approximation, which implies using a constant collision probability that will result in an inaccurate throughput analysis.

We used our model to evaluate the throughput performance of ECRA and compare it to those of BEB and EIED. Our analytical model provided an accurate calculation of the probability that a station transmits in a random time slot (τ), which reflects the network size. To evaluate saturation and maximum throughput for ECRA and the benchmark algorithms, we implemented our model for ECRA, BEB, and EIED.

The theoretical analysis results showed that our model provided an accurate throughout analysis of ECRA, BEB, and EIED. The theoretical results showed that ECRA increased the channel access time, probability of successful transmissions, saturation, and maximum throughput compared to BEB and EIED.

The main challenge faced by our analytical model is to extend it to operate under unsaturated conditions since saturated conditions rarely apply in real-life networks. We also highlight the need to extend our algorithm to operate under non-ideal conditions such as packet lost and the the hidden station effect.

Finally, simulation and theoretical results proved that our algorithm, ECRA, performs better than BEB and EIED in terms of throughput. The theoretical and simulation results projected that ECRA throughput performance endured the increased number of stations more than BEB and EIED. Accordingly, we conclude that ECRA is more suitable to operate in dense networks than BEB and EIED.

5.2 Future Work

In this section, we highlight a number of research directions that can be followed for future developments.

We aim to study the behaviour of our algorithm in dense networks where the number of stations exceeds 100. In this thesis, we evaluated the performance of ECRA in environments containing up to 50 stations; we project that ECRA would perform better in dense environments since its performance in terms of throughput significantly improved as the number of active stations increased. One future direction of our research is to present simulation results showing the performance of ECRA in highly dense and dynamic networks such as Vehicular Ad-hoc Networks (VANETs) and Mobile Wireless Ad-hoc Networks (MANETs).

Another direction for future development is taking into consideration the station's transmission history, whereby we are able to improve jitter and delay results. We can achieve this by including parameters that can be collected locally by the station without monitoring the channel. The number of successful and failed transmissions can be used to calculate a dynamic CW increment/decrement to replace the exponential one.

Regarding analytical modelling, we consider an extension of our model to evaluate throughput for IEEE 802.11 DCF under unsaturated conditions. Since unsaturated conditions are applicable to several types of applied networks, this will allow us to use our model in many future scenarios.

We also aim to extend our model to analyse IEEE 802.11 DCF using a variable bit rate rather than a constant one. This approach should enable us to apply our model to real-time applications such as traffic controllers, environmental research, and autonomous vehicles.

5.3 Final Remarks

The motivation behind this research came from our belief that dynamic networks are the future of our life. By studying the current standard and its many proposed extensions, we observed the complexity in addressing the fundamental nature of WANETs. We therefore developed our algorithm, ECRA, and were able to prove, through simulation and theoretical analysis, that our contribution would improve the performance of DCF, in terms of throughput, in future applications.

We were further inspired by the research conducted on Markov chain-based analytical models. This research led us to the development of an accurate presentation model of the most significant parameters of WANETs. We were successful in constructing a model that can reflect the network conditions without any complex computations.

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